THE EFFECT OF NITROGEN INJECTION ON SPECIES CONCENTRATION AND TEMPERATURE DISTRIBUTION IN A FLAT FLAME

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THE EFFECT OF NITROGEN INJECTION ON SPECIES CONCENTRATION AND TEMPERATURE DISTRIBUTION IN A FLAT FLAME

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NOMENCLATURE

A_n	measured area signal from component n
A_n^c	measured area signal from V_n^c
atm	atmosphere
d	diameter of thermocouple bead
e	gas emissivity
E	thermocouple emissivity
I.D.	inside diameter
$\dot{m}_{air}$	mass flow rate of air
$\dot{m}_{CH4}$	mass flow rate of CH_4
$\dot{m}_{N2}$	mass flow rate of N_2
N	constant
P_b	barometric pressure
p_{CO2}	partial pressure of CO_2
p_{H2O}	partial pressure of H_2O
p_{N2}	partial pressure of N_2
p_{O2}	partial pressure of O_2
p_v	vapor pressure
$p_{v,sat}$	vapor pressure at saturation
t_c	temperature of thermocouple
t_m	mean temperature
t_w	temperature of the chimney wall
V	velocity of gas
V_n	volume of sample component n

V_n^c	volume of component n used for calibration to give an area signal of A_n^c
$\dot{V}_i$	volumetric flow rate of species i
ϕ	relative humidity
Φ	equivalence ratio

Subscripts

m	mean
n	any component
v	vapor
w	chimney wall

Superscripts

c	calibration

SUMMARY

The main objectives of the research work are: (i) to produce a workable system for the quantitative measurement of species concentration profiles and temperature profiles which will incorporate a gas chromatograph, mass spectrometer and associated instrumentation and (ii) the development of techniques and procedures for the calibration of the gas chromatograph and the mass spectrometer. Once the system and procedures have been developed a technique can then be established for extracting gas samples from a flat flame and for establishing the species concentrations and temperature profiles of the mixture.

The method of solution was to systematically add to and improve an apparatus available in the laboratory that would perform the required tasks. Then by using certain techniques and procedures a calibration method was to be established.

For the flat-flame burner methane was chosen as the fuel to premix with the oxidizer (air) in the mixing chamber. The mixed gases are discharged through a porous bronze plate and form the flat flame at the top of this plate. Nitrogen was chosen as the gas to impinge on the flat flame from the opposite direction. Equivalence ratios of 0.65 and 0.90 were selected for the premixed flame.

In general, after many trials, a workable system was developed that incorporated a gas chromatograph and mass spectrometer. After successfully producing a technique to calibrate the system, actual gas samples were extracted and temperature measurements and species concentrations of O_2, N_2, CO_2, H_2O were obtained in ten and six horizontal planes, respectively, ranging between 1/16 inch and 2 inches above the top of the burner matrix.

CHAPTER I

INTRODUCTION

Significance of Flame Research

Since the dawn of man, combustion has been his major source of harnessed energy. In today's world combustion is still the front runner as an energy source although nuclear energy is slowly gaining in importance. Up until a few decades ago very little was known about combustion because of its very complex nature. Since World War II a large amount of research has been accomplished in the field of combustion, however, many new techniques must still be developed and refined, since the old techniques in many cases are inadequate.

In the School of Mechanical Engineering at the Georgia Institute of Technology a continued effort has been made to study the flat flame. By understanding the phenomena that takes place in this flame one can better understand what occurs in other types of flames. In turn, this knowledge will further our understanding for some of the combustion processes.

Once an efficient burner system has been developed, it is then necessary to perfect an apparatus that is capable of extracting information from the burner's flame that will

be useful in interpreting what is actually happening in the combustion process. With the aid of mass spectrometers, gas chromatographs, precision electrical and electronic equipment, computing machines and high-purity commercial gases, we are now able to get a better picture of what is taking place in the flame. However, the complexity of this equipment requires precise procedures to be developed. The calibration of such equipment is also of equal importance and if the equipment is not calibrated properly the results will be meaningless.

The research studies with the flat flame in the School of Mechanical Engineering at the Georgia Institute of Technology have been carried out with the intent to develop needed procedures and techniques in flame measurements. It is to this end that the research reported in this thesis was carried out.

Previous Efforts and Accomplishments

The initial work on the flat flame burner at Georgia Tech started with Shakill [1] who designed and tested the burner located in the Fire Hazard and Combustion Research Laboratories of the School of Mechanical Engineering. The burner utilized a flat methane-air flame and had incorporated an opposed gas-particle jet. Most of Shakill's work was involved with the burner design and temperature profiles of the working system.

The next step was taken by Fisk [2] who used the same burner with an opposed aluminum particle jet using nitrogen as a carrier gas. He carried out comparative measurements of temperature profiles and also measured particle velocities for a wide range of air-fuel ratios and particle flow rates.

The next logical step in the research of the flat flame would be to take gas samples of the stable species and measure their concentrations along with temperature profiles. This is what was accomplished in the present research.

Purpose and Statement of the Problem

The purpose of this thesis is to develop an experimental technique for extracting gas samples from a flat flame and to measure the species concentrations and temperature of the mixture. The problem to be solved for satisfying the above stated objective is composed of two parts: (i) the design, construction and assembly of a workable system which will incorporate a gas chromatograph, a mass spectrometer and associated instrumentation for the quantitative measurement of species concentration profiles and temperature profiles, (ii) the development of techniques and procedures for the calibration of the gas chromatograph and the mass spectrometer.

Once the above problem has been solved, the system can then be used to determine the effects of nitrogen gas injected in an opposed flow configuration on the flat

methane-air flame.

Literature Survey

This literature survey will be concerned with: (1) the measurement of temperature and species concentrations in a flame and (2) the effects of N_2 injection into the flame. Methods and definitions will be discussed.

Temperature Measurements

There are three basic methods for measuring temperatures in the flame. These methods are: probe thermometry, radiation thermometry, and flame gas density determinations. The advantages of using a thermocouple probe for temperature measurement are: (1) high resolution and little aerodynamic disturbance can be obtained by using a small diameter thermocouple; (2) since the measurements are electrical in nature a high precision can be obtained; and (3) thermocouples, if made from the right material, can withstand high temperatures.

In measuring temperatures with a thermocouple in a flowing stream of hot gases, three sources of error exist. These are errors through radiation, conduction and temperature lag.

Fishenden and Saunders [3] have presented an effective method for calculating errors in gas temperature measurements. They state that the greatest part of the error evolves from the exchange of radiation between the thermocouple and the surrounding walls, the conduction of heat

along the thermocouple leads, and the lag between the thermocouple and the gas temperatures when the gas temperature fluctuates. Another source of error is from emission and absorption of radiation by the gas. Since the diameter of the bare thermocouple leads is small and the burning gas velocity is high enough to create a steady flame without many fluctuations, the only error that will be considered in this thesis is the one due to radiation between the thermocouple and the surrounding walls.

The second method stated above for measuring the temperature in a flame is radiation thermometry. The two advantages of this technique are: (1) it does not disturb the system being studied and (2) there is no high-temperature limit. The principle disadvantages are: (1) poor spatial resolution and (2) it produces an average over the entire path length used [4]. The low-temperature limit of this method is set by the capability of the optical system in measuring a low intensity light emitted from the flame. Due to the geometry of the flat flame, it would be difficult to optically probe the homogeneous regions of the flame.

The third method for measuring flame temperature is by gas density determinations. The advantages to using this technique are: (1) moderate precision and spatial resolution, (2) the system is not disturbed and (3) there is no upper temperature limit with certain methods. The disadvantages, depending on the method used, are: (1) complicated data

reduction, (2) requirements of average-molecular-weight information, (3) upper temperature limits with the pneumatic probe method, (4) nonequilibrium emissions, (5) restriction to relatively high temperature regions when using emissivity and spectroscopic measurements and (6) the high cost of the equipment [4].

A comparison of the different techniques shows that for the most part, their agreement is good [4]. For this thesis the thermocouple method was chosen, since for the temperature ranges to be encountered, it is the system best adaptable and the simplest method of the three discussed above.

Species Concentration Measurements

There are two basic methods used for the determination of stable species concentrations. These two methods are: (1) probe sampling followed by analysis and (2) analysis by spectroscopic means [4].

The first method to be discussed is the probe sampling method. This consists of withdrawing the sample from the flame, quenching the sample and analyzing it. As the gas sample is withdrawn from the flame it may then be stored in a container for later analysis, known as batchwise sampling or an analytical instrument may be inserted into the system so a continuous-flow sampling can take place. The continuous-flow method is best where adsorption on the container walls takes place. Quenching the sample is best obtained by the

use of a tapered quartz microprobe with a small sonic orifice inlet. The decompression created by the microprobe and its connecting tubing is what quenches the gas.

There are then three techniques that can then be used to analyze the gas sample. The first technique is the use of the Orsat analysis which not only makes use of the gas laws but also the physical and chemical properties of the gases being studied [4]. The advantages of this technique are that it is inexpensive, simple and only a small sample of up to a few cm^3 atm is required. The disadvantages of the Orsat analysis are: (1) it is a slow process and (2) the components must have appreciable vapor pressure at room temperature.

The second technique of analyzing the gas is by mass spectral analysis. There are two major types of mass spectrometers. They are: (1) the conventional magnetic deflection spectrometer and (2) the "time-of-flight" spectrometer. The first type of mass spectrometer is based on the principle that with controlled electron bombardment, a molecular species will produce a reproducible distribution of ions which can be separated from one another by accelerating them electrostatically through a perpendicular magnetic field [4]. The advantage of this type of instrument is that there is good resolution and high sensitivity. The main disadvantages are: complexity, high costs and the fact that it is not very versatile. The second type of mass

spectrometer mentioned above differs from the first type because the ion separation is obtained in time rather than space [4]. The advantage of this instrument is its extreme rapidity in scanning a spectrum. However, its precision and sensitivity is inferior to the magnetic deflection spectrometer.

The third technique that may be used for the analysis of the gas is known as chromatography. In this technique a certain size sample is injected into a flow system with a carrier gas. As this goes through the column the different species will show different residence times which depend on their adsorptive properties. As a result, certain species will be separated out. The type of column used will depend on what species are to be analyzed. As the species come out of the column they then must go through a detection device which may utilize any of the following modes: thermal conductivity, ionization, density balances and mass spectral analysis. The advantages of using a gas chromatograph are: analytical accuracy, moderate rapidity, high sensitivity, high selectivity and small sample size [4].

The fourth technique to analyze the gas is known as absorption spectroscopy. This is a comparative technique which measures the loss of intensity of a beam of radiation due to the gas sample being inserted into the path of the beam [4]. This method is precise and lends itself as a convenient analytical tool for flame studies. The main

disadvantages are: the need to work with single absorption lines of low strength and the sample size needed for most commercial instruments is usually inconveniently large and much greater than the sample size needed for the Orsat analysis.

The second basic method, as stated above, used for the determination of stable species concentrations is "in situ" analysis by spectroscopic means. This method is not applicable to all species and is mostly used for measurement of unstable species. Absorption spectroscopy is an excellent method because it does not disturb the system. The main problem with using this method to determine the concentration of radicals is that of determining quantitative concentrations. This creates a need for careful calibration of the system which is very difficult. For use with stable species there is not much of a problem provided that there is a large enough region for measurement and provided that light intensity of the flame is high enough.

N_2 Injection into the Flame

It has been shown in past literature that nitrogen can be used as an inhibitor [5]. However, most of the work done in the past on inhibitors only demonstrate how they retard the burning velocity and how they may change the temperatures in the various flame zones. The effect of inhibitors on the preignition zone is still, to a great extent, unknown. It is believed that inhibitors perform as

chain breakers and reduce the concentration of free radicals in the flame such as H, O and OH which are important to the propagation reactions [5]. Wilson [6] investigated the structure of a methane-oxygen flame which was inhibited by CH_3Br. He measured flame temperature and composition profiles. He concluded that there was a prolongation of the preignition zone and a shift of the primary reaction zone to a higher temperature.

Wagner [7] has done a great deal of work on the effect of many inhibitors on the burning velocity of n-hexane and air mixtures. He found that if he had a stoichiometric n-hexane-air mixture with a burning velocity of 42.5 cm/s then it would require 8% by volume of N_2 in order to reduce the burning velocity by 30%.

Scope of the Thesis

As stated above, the main objective of this thesis is to develop a system for extracting gas samples from a flat flame and experimental techniques with existing mass spectrometer and gas chromatographic instrumentation to measure the concentration and temperatures in the burner flow field. This will then lead to some experimentation on how N_2 injection effects the flame in regards to temperature and concentration changes.

A discussion on the instrumentation and equipment is presented in Chapter II along with a detailed description of needed changes in the designs. Chapter III follows with an

explanation of the experimental procedures along with initial groundwork and calibrations needed. The results are discussed in Chapter IV. This chapter contains representative graphs of concentration and temperature profiles showing what the newly designed system produced. The conclusions and recommendations then follow in Chapters V and VI, respectively. Appendix A contains the calibration curves for the flow meters. Appendix B contains the remaining bulk of the temperature and concentration profiles, sample calculations and chemical equations.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

Purpose and Design Criteria

An apparatus called the Flat Flame Burner with an Opposed Gas Jet was designed and built [1,2] to:

(i) burn a mixture of air and methane at various air/fuel ratios and flow rates,

(ii) measure the temperature of the mixture at various points in the flame, and

(iii) extract and analyze gas samples from the flame at various points.

The major design criteria which had to be met by the apparatus are (1) provide a thorough mixing of the gases before ignition, (2) incorporate an accurate means of moving the temperature and gas sampling probes both vertically and horizontally in the flame, (3) prevent water vapor condensation in the apparatus so as to insure reliable results in species concentration measurements, and (4) provide calibration of the mass spectrometer for each gas species.

Major Components and Operating Principles

There are five major components of the apparatus used for the conduct of the research presented here. These components are: (1) the burner assembly, whose function is

to mix and burn the gases, (2) the traversing mechanism, employed to introduce the various probes into the flame at different locations, (3) the gas flow system, utilized to introduce and control the various gases at different ratios and flow rates, (4) the flame temperature instrumentation, used to measure and record the flame temperature at various points in the flame, and (5) the gas sampling system, used to extract gases from various locations in the flame, and to analyze and record the concentrations of each species. In the following sections the five major components of the apparatus will be discussed to present their design and operating principles.

Burner Assembly

The burner, as shown in Figure 1, was designed and built by Shakill [1]. The methane and air enter at the bottom of the mixing chamber (items 11 and 12). The chamber (item 10) is made from a steel pipe which is 24 inches long and has a 10 inch I.D. Inside the upper section of the chamber are located six 200 mesh stainless steel screens (item 9) which are placed 1.5 inches apart from each other. A cast aluminum transition piece (item 8) connects the mixing chamber to the brass burner tube. The burner tube is 14.5 inches long and has a 3.28 inch I.D. Close to the bottom of this tube is a 30 mesh stainless steel screen. From this point the tube is filled with 3 mm diameter glass beads

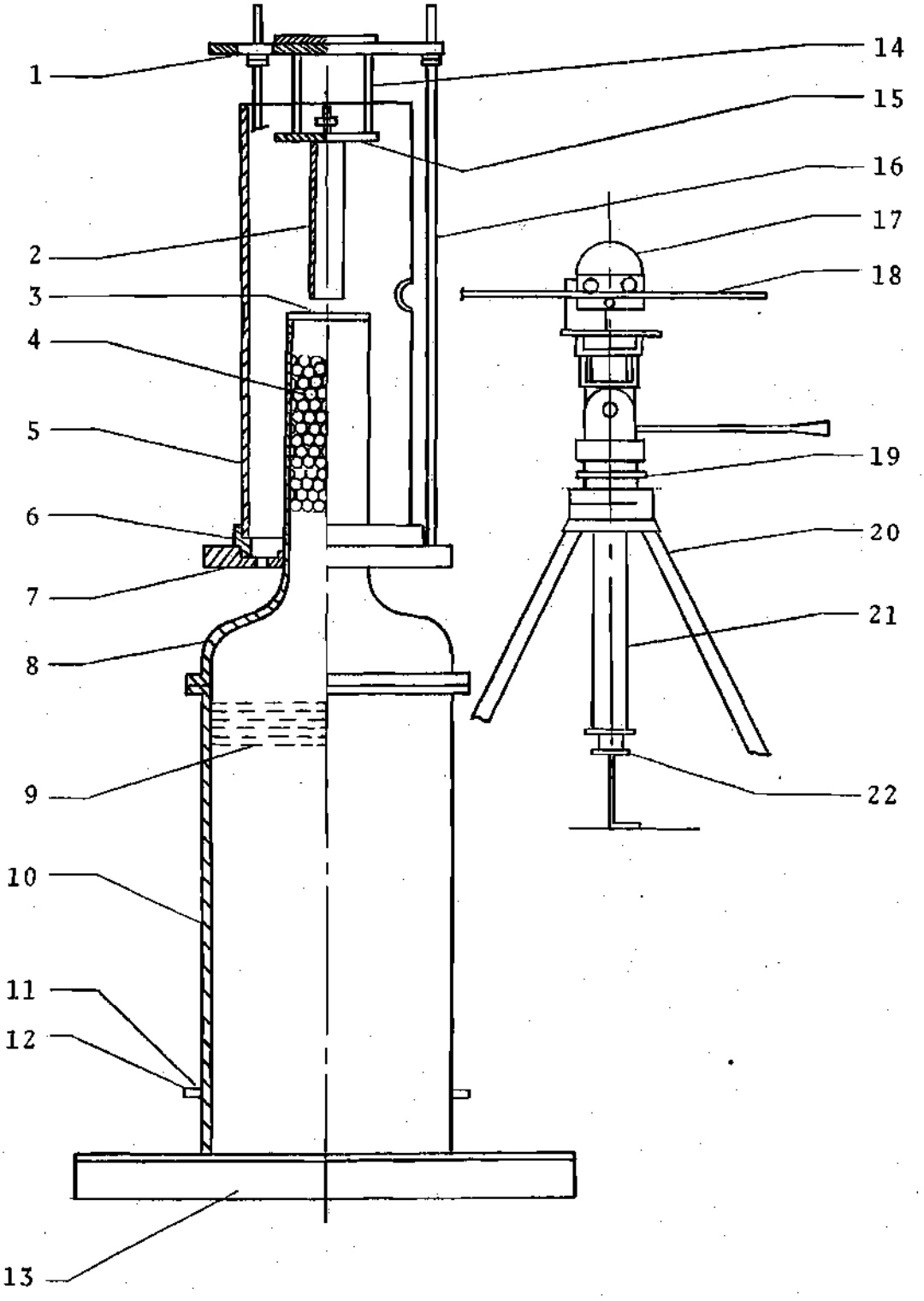

Figure 1. Schematic of the Burner Assembly and Traversing Mechanism

Key for Figure 1

1. Steel Support Ring
2. Stainless Steel Injection Nozzle
3. Sintered Bronze Porous Disc
4. Glass Beads 3 mm in Diameter
5. Pyrex Glass Chimney
6. Aluminum Support Ring
7. Aluminum Support Ring
8. Cast Aluminum Transition Piece
9. 200 Mesh Stainless Steel Screens
10. Steel Pipe
11. Methane Inlet
12. Air Inlet
13. Burner Base Support
14. Extension Rods
15. Steel Support Plate
16. Steel Support Rods
17. Variable Speed Drive Motor
18. Probe Holder
19. Threaded Aluminum Spacer Assembly
20. Tripod
21. Tripod Tube
22. Anti-Rotation Assembly

(item 4) up to 3.5 inches from the top of the burner tube. These beads are used for a final gas mixing and also to obtain an even flow of gas.

At the top of the burner tube, a sintered bronze porous disc (item 3) is held in place by a bronze ring and three set-screws. This disc is used as the flame holder and at the same time it prevents flash-back.

The opposed nitrogen jet assembly is located above the burner. The gas enters through a 1/8 inch diameter inlet tube which connects up with a stainless steel injection nozzle (Figure 1, item 2). The injection nozzle is 12 inches long and has a one inch I.D. This nozzle is supported by a steel plate (item 15) which is connected to a steel support ring (item 1) by three extension rods (item 14). The opposed gas jet assembly is held in place by three steel support rods (item 16) which are 0.5 inches in diameter and 34 inches long. These three rods are, in turn, held in place by an aluminum support ring (item 7) attached around the top of the cast aluminum transition piece. Thus, the jet assembly design makes it possible for the injection nozzle exit to be located at different heights above the top of the sintered bronze disc by means of six 3/8 inch leveling nuts on the support rods (item 16).

A pyrex glass chimney (Figure 1, item 5) encloses the injection nozzle and burner tube. This chimney is 24 inches long and has a six inch I.D. The chimney is supported by

aluminum support rings (item 6) of various heights. Thus, by using different combinations of these rings one could adjust the height of the pyrex chimney to many different positions. This was a new design which allowed for greater flexibility in vertical movement of the probes. A two inch diameter port hole in the chimney provides access to the hot gas region of the burner for temperature and species sampling of the flame with the thermocouple and sampling tube probes respectively. An asbestos fiber material was used to cover the chimney opening and at the same time allow the traversing of a thermocouple or sampling probe by means of a small slit cut in the material.

In summarizing, the burner assembly was constructed as a means of mixing the combustible gases in the mixing chamber, burning them on the sintered bronze disc, and introducing the nitrogen gas through the opposed gas jet assembly. The pyrex chimney was used to create an arena that would not be disturbed by the outside air currents.

Traversing Mechanism

The traversing mechanism is used to hold the temperature and gas sampling probes in place. Once in place, the mechanism could then move the probe to a new position in either a vertical or horizontal direction.

The mechanism mainly consists of a tripod (Figure 1, item 20) with a variable speed drive motor mounted on top (item 17). This motor is controlled by a DISA type 52B01

sweep drive unit. Two alterations were designed for the tripod. The first alteration consists of a threaded aluminum spacer assembly (item 19) with 40 threads per inch. This is used to provide fine height adjustments. A scale mounted on the assembly allows one to measure a change in height of 0.025 inches or more. The second alteration is an anti-rotation assembly (item 22) at the bottom of the tripod to prohibit the tripod tube (item 21) from rotating when being adjusted vertically. This anti-rotation assembly consists of a hollow threaded screw with a lock nut on it. This screw fastens to the bottom of the tripod tube. Fitted into the hollow screw is a rectangular aluminum shaft which is fastened to the base table.

A third alteration was incorporated for the traversing probe holder (item 18). This consisted of exchanging the regular traversing rod with a toothed traversing rod and a pinion drive shaft purchased from the manufacturer. This combination keeps the rod and probes from rotating and slipping.

Gas Flow System

The gas flow system for the combustible and inert gases is shown schematically in Figure 2. There are two gas cylinders, one of which contains CH_4 and the other N_2. The gas flow is regulated from these cylinders by means of two-stage pressure regulators for each cylinder (item 12). The

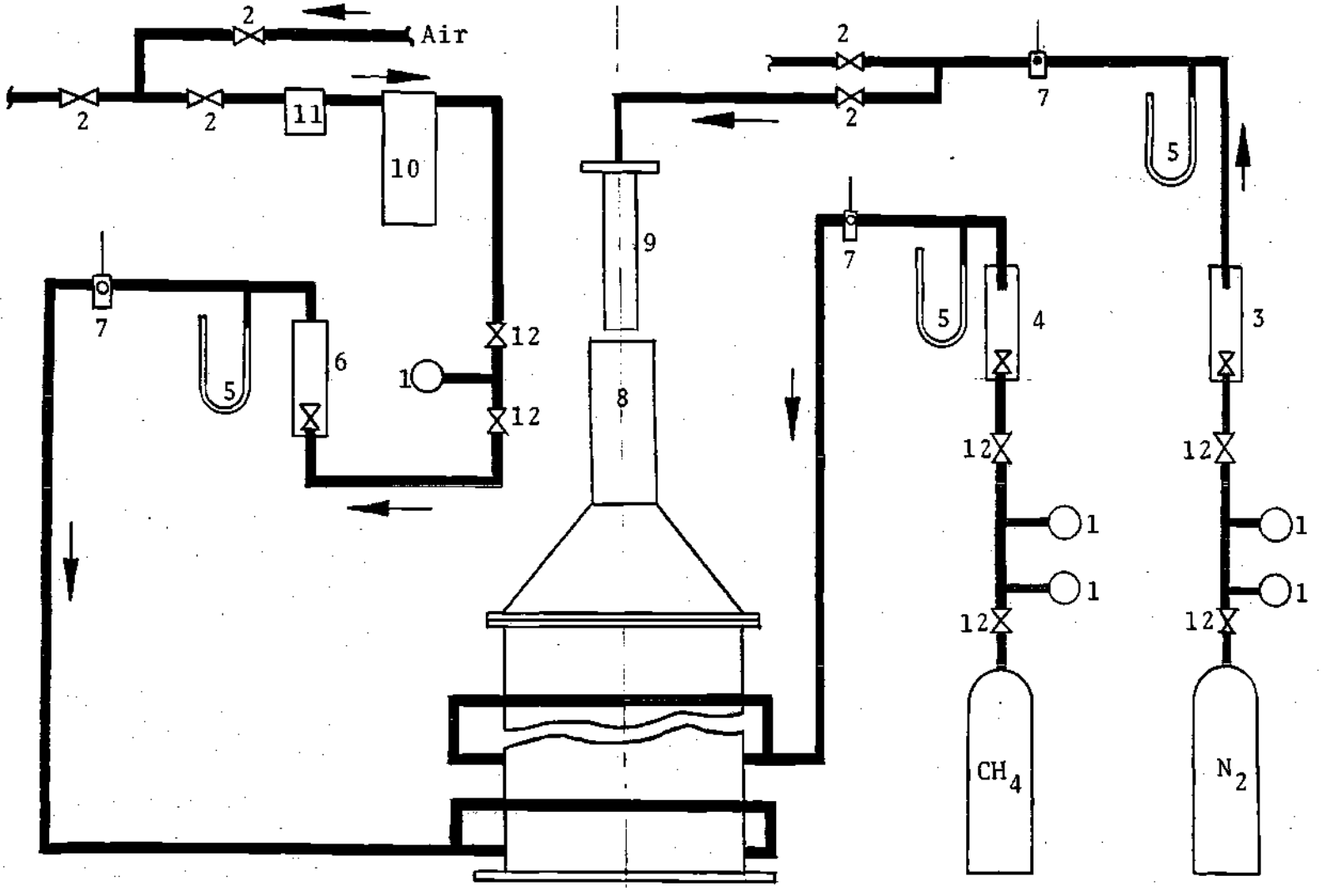

Figure 2. Schematic of the Flat Flame Burner with Air, Fuel and Nitrogen Flow Paths

Key for Figure 2

1. Pressure Gage
2. Hand Valve
3. Nitrogen Flow Meter
4. Methane Flow Meter
5. Manometer
6. Air Flow Meter
7. Thermometer
8. Burner
9. Nitrogen Injection Nozzle
10. Desiccator
11. Particle Filter
12. Pressure Regulator

down stream stage of the regulator is used for fine control of the pressure. The pressure is monitored by a pressure gage (item 1) for each regulator. The volumetric flow rate is measured by flow meters (items 3 and 4), one for each gas. For the methane gas, a Brooks flowmeter was used with a stainless steel float and tube number of 3-15-4. For the nitrogen gas, a Brooks flowmeter was also used with a glass float and a tube number of R-6-15-B. The calibration curves for these two flowmeters are included in Appendix A. Downstream from the flowmeters are located manometers for each gas (item 5). The manometer for CH_4 measured the pressure in inches of a known oil. The manometer for N_2 measured the pressure in inches of Hg. In addition, downstream from the flowmeter a thermometer (item 7) was used to measure the temperature of the gas. From this point, the CH_4 was allowed to proceed into the burner mixing chamber and the burner tube (item 8). The N_2 is further controlled by a hand valve (item 2) before it can proceed into the nitrogen injection nozzle (item 9).

The air to the burner passes first through two hand valves (item 2), then through a particle filter (item 11) and next dried in a desiccator (item 10). The air pressure is to be regulated by a single stage pressure regulator (item 12) and the downstream pressure monitored by a pressure gage (item 1). The volumetric flow rate is then measured by a Brooks flowmeter with a carboloy float and a tube number of

R-6-15-B. The calibration curve is in Appendix A. Downstream of the flowmeter is a manometer which measures the air pressure in inches of Hg and a thermometer (item 7) to measure the air temperature.

Thus, by using the above described system two combustible gases can be regulated, mixed, and burned in the burner. A third gas can also be regulated, monitored and injected into the flame in an opposed jet configuration.

Flame Temperature Measuring System

All gas temperatures in and above the reaction zone were measured by using a system as shown in Figure 3. The wall temperature of the pyrex chimney (item 1) was measured by a chromel-alumel thermocouple (item 5) which had a junction of 0.040 inches in diameter. The flame temperature was measured with an Omega platinum vs. platinum-13% rhodium thermocouple which had a junction diameter of 0.010 inches (item 2). An Omega ice point cell (item 6) provided the low temperature reference for both of the thermocouples. It was maintained at 32°F. The Leed and Northrup millivolt potentiometer (item 7) served two purposes. It was used to measure the chimney wall temperature and it was also used to calibrate the X-Y plotter (item 8) by supplying a reference voltage. As the temperature profiles in the hot gas region of the burner were measured using the traversing probe thermocouple they were recorded on an X-Y plotter (item 8). The position of the thermocouple was also monitored and recorded on the

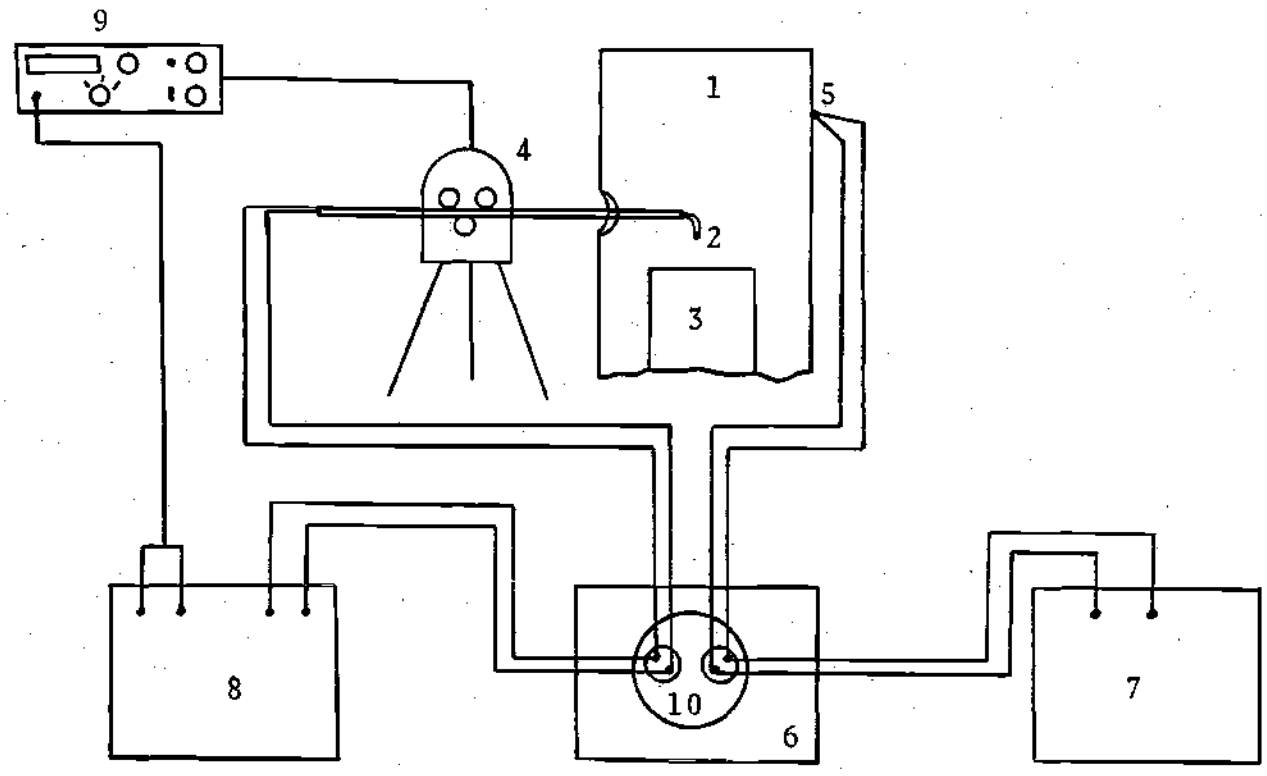

Figure 3. Schematic of Instrumentation for Flame Temperature Measurements

Key for Figure 3

1. Pyrex Chimney
2. Traversing Thermocouple (flame temperature)
3. Burner
4. Stepper Motor
5. Thermocouple (wall temperature)
6. Ice Point Cell
7. Millivolt Potentiometer
8. X-Y Plotter
9. Sweep Drive Unit
10. Thermocouple Cold Junctions

X-Y plotter by signals sent to it from the sweep drive unit (item 9). This unit was used to control the speed and direction of the stepper motor (item 4) which, in turn, controlled the position of the thermocouple probe.

Gas Sampling and Analysis System

The system designed for gas sampling and analysis is schematically shown in Figure 4. The quartz microprobe (item 16) was one of the key elements in the system. The probe was made of quartz glass to withstand the temperatures encountered in the present burner and in view of its non-catalytic behavior even at high temperatures. This probe was also a critical flow probe and it has good quenching abilities. This probe was specially constructed to specifications given by Fristrom and Westenberg [4].

The wire heating coils, shown in Figure 4, were used to heat all of the stainless steel tubing. This kept the water from condensing in the flow tubes. A stainless steel sleeve (item 12) over part of the microprobe was also heated by the coils. This sleeve extended to about 1.25 inches from the inlet orifice. The sleeve, in turn, was used to heat the probe in areas that are too hot to use the heating wire. The energy supplied to the heating wires was controlled by variable autotransformers and monitored by a voltmeter and an ammeter (item 3).

The flow of gas going to the mass spectrometer and gas

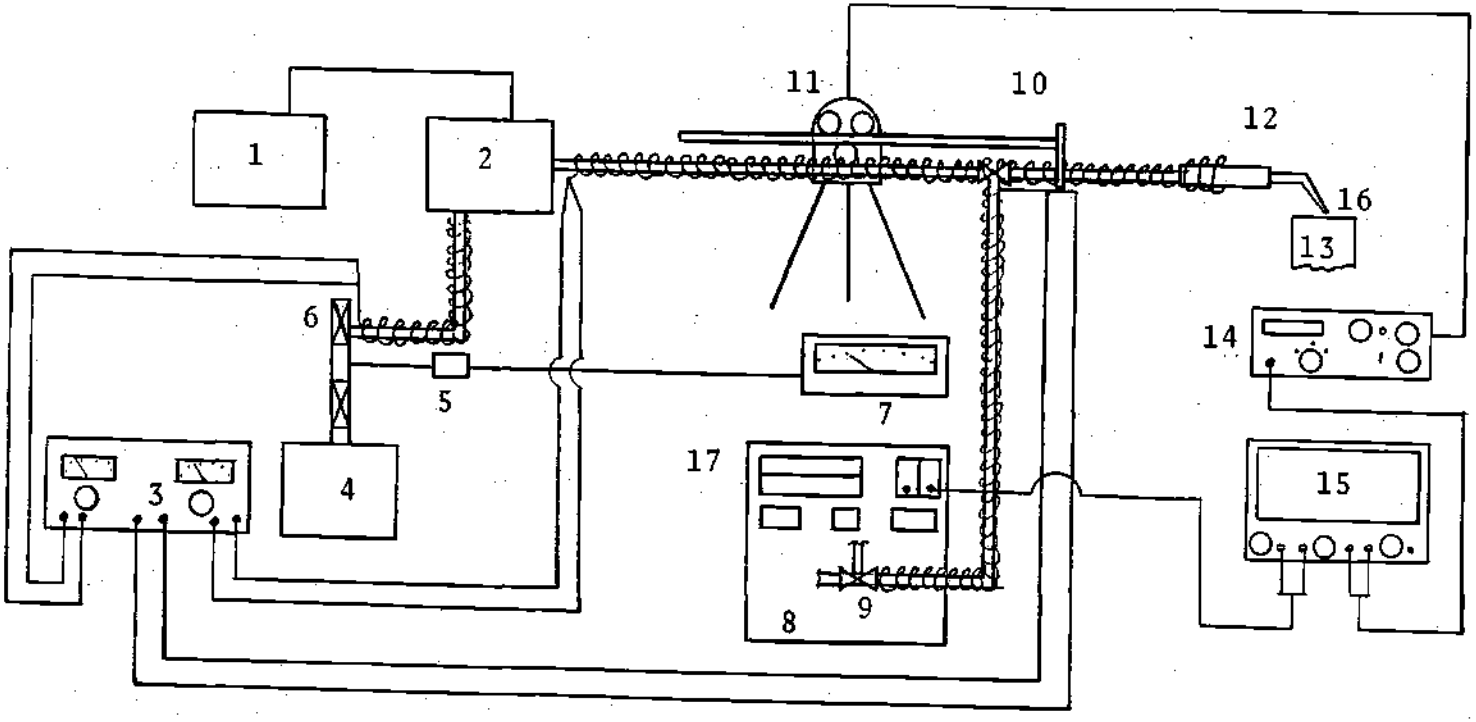

Figure 4. Schematic of Instrumentation for Gas Sampling and Analysis

Key for Figure 4

1. Recorder with Area Integrator
2. Gas Chromatograph
3. Sampling Tube Guard Heaters Control Power Pack
4. Vacuum Pump
5. Vacuum Thermistor Gage
6. Micro-Metering Needle Valve
7. Vacuum Thermistor Gage Meter
8. Mass Spectrometer
9. Micro-Metering Needle Valve
10. Micro-Metering Needle T-Valve
11. Stepper Motor
12. Steel Sleeve
13. Burner
14. Sweep Drive Unit
15. X-Y Plotter
16. Quartz Microprobe
17. Two-pen Strip Chart Recorder

chromatograph was controlled by a micrometering needle T-valve, (item 10). Adjustment of this valve ensured each analyzer of getting the proper amount of gas it needed to operate properly.

A stepper motor, (item 11), was used to move the quartz probe. This motor was capable of moving the probe both forward and backward. A DISA type 52B01 sweep drive unit, (item 14), was used to control the motor. As the probe moved its position was recorded by an X-Y plotter, (item 15), which was electrically tied into the sweep drive unit. Slippage was kept to a minimum by the use of a pinion wheel which meshed with a pinion drive shaft.

A vacuum pump, (item 4), was used to reduce the pressure in the system in order to pull the combustion gases into the system. The flow of gas into the pump was controlled by a micrometering needle valve, (item 6). The vacuum which the pump created was detected by a Kinney vacuum thermistor gage (model KTPG-1), (item 5). A vacuum thermistor gage meter, (item 7), was used to monitor the amount of vacuum detected by the thermistor gage.

A Beckman 1GC-2A gas chromatograph, (item 2), was used as one means of gas analysis. The carrier gas used was helium. When analyzing N_2 and O_2 a molecular sieve column was used. A silica gel column was used to analyze CO_2. As the species came out of the column they then went through a detection device which utilized thermal conductivity to

determine the amount of each species present. Signals from this were then sent to a Beckman recorder with an area integrator, (item 1). This device recorded and measured the amount of certain gases detected.

The other instrument used to analyze the gas was a Varian mass spectrometer, (item 8). The flow of gas into the mass spectrometer was regulated by a micrometering needle valve (item 9). A 7702 B Hewlett-Packard strip chart recorder (item 17) was used to record the amounts of species detected by the mass spectrometer. The X-Y plotter (item 15) also was used to record the amount of the species detected. The mass spectrometer was a conventional magnetic deflection spectrometer. Once the sample enters it is bombarded by an electron beam from a heated filament. The ions produced are then accelerated by a set of electrodes in the crossed magnetic field. The ion path has a radius of curvature which is a function of the mass-to-charge ratio, or "mass number." Ions with a certain charge-to-mass ratio can be selected by the use of collimating slits. A signal, which is proportional to the partial pressure of the molecular species parent to the ion, is produced from a current which is generated by the ions impinging on a target electrode [4]. Thus, by the selection of different mass numbers various species could be detected.

The actual test procedures for temperature measurements, gas sampling and gas analysis with the equipment

described above will be discussed in the next chapter. Calibration techniques, data reduction and results will be presented in Chapter IV.

CHAPTER III

PROCEDURE

Gas Flow System

In order to satisfy the purpose of this thesis a flat flame had to be established which could be used to test the temperature and species concentration measurement techniques to be developed. Initially it was decided to use a high and a low flow rate, each at the rich and lean limits of the flame. To establish the rich and lean ratios and the appropriate flow rates that could be used, a range of air-fuel ratios were produced at each flow rate with the following procedure. First the air flow rate would be set and then the methane flow rate would be raised until the flat flame changed to a conical flame. This would establish a rich limit. Next, the methane flow rate would be reduced until the flat flame started to lift off the matrix. This would then establish a lean limit. This procedure was repeated for a range of air flow rates until a graph of mass flow rate of CH_4 vs. mass flow rate of air could be plotted showing the rich and lean limits of the flat flame as shown in Figure 5. Then, lines of constant equivalence ratio, Φ, were plotted on this graph. After studying the graph it was decided to use a Φ of 0.90 and 0.65 because

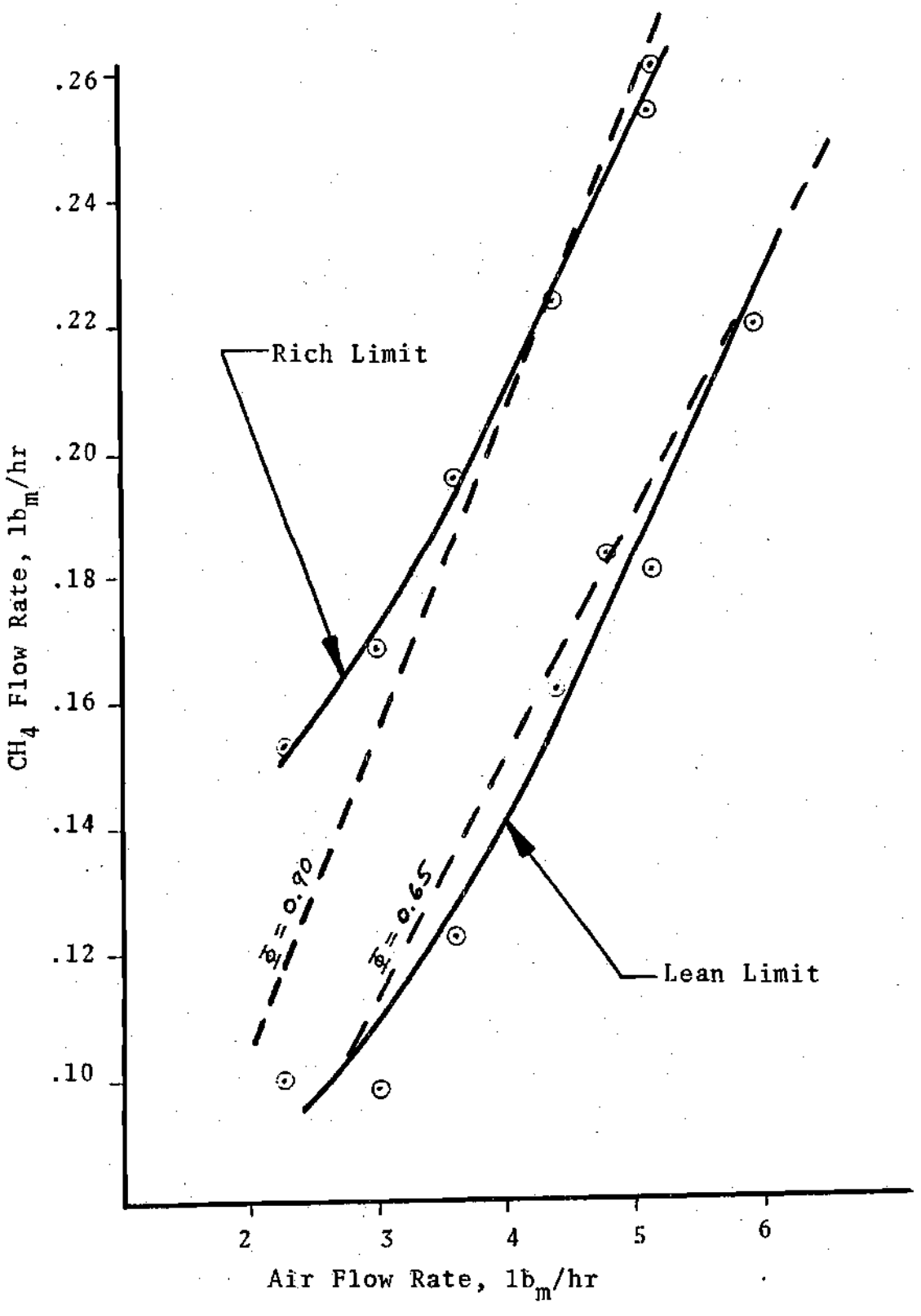

Figure 5. Flat Flame Limits

both fell within the flat flame limits and a well separated high and low flow rate could be obtained at both values of the equivalence ratio. At a Φ of 0.90 the low flow rate was established by an air flow of 2.23 lb_m/hr and a methane flow of 0.12 lb_m/hr. The high flow rate was created by an air flow of 4.14 lb_m/hr and a methane flow of 0.22 lb_m/hr. At a Φ of 0.65 the low flow was established by an air flow of 2.88 lb_m/hr and a methane flow of 0.11 lb_m/hr. The high flow was created by an air flow of 4.84 lb_m/hr and a methane flow of 0.18 lb_m/hr.

Once the type of flame was established the next step was to determine the position of the nitrogen injection nozzle exit above the burner matrix and the usable range of the nitrogen flow rates. After numerous experiments it was found that for the low flow rates of air and methane, a flow of 0.20 lb_m/hr of nitrogen was the highest flow that could be used without blowing the flame off the matrix. At the high flow rates of air and methane it was found that a flow of 0.20 lb_m/hr of nitrogen could hardly be detected. Thus, a flow of 1.28 lb_m/hr of nitrogen was used in order for it to be readily detected.

The height of the injection nozzle was also a critical factor. After using the nozzle at various heights it was decided to fix the nozzle at 0.50 inches above the burner matrix. At this height nitrogen could be detected in all flames and, at the same time, it would provide enough room

for the probes to traverse the flame without being interfered with by the nozzle.

Calibration of the flow meters was also a necessary step in preparing for this investigation. This was accomplished by using the bubble method. A graduated glass tube of 1 cm in diameter and 50 cm^3 calibrated volume was placed in series with the flow meter. A soap bubble introduced into the tube was timed as it traversed the 50 cm^3 volume at different flow rates. The calibration curves are shown in the Appendix A (Figures 17-19).

Temperature Measurements

In order to obtain accurate temperature measurements the speed at which the temperature probe should traverse the flame had to be determined. If the flame is traversed too fast a time lag problem might develop where the position of the probe may not correspond to what is being recorded. As a result, a hysterisis type of curve is generated. After experimenting with all of the sweep drive settings it was found that 1 min/volt provided the best compromise for good results. At this setting the probe traversed the matrix at a rate of about 0.6 inches per minute.

Another problem which had to be solved before any accurate results could be obtained was the determination of what size thermocouple to use. It was found, as expected, through experimentation that the larger the thermocouple

bead the less sensitive it was to changes in temperature. However, when the thermocouple wire and junction were too small the flame would cause the junction to vibrate excessively. After experimenting with several types and sizes it was decided to use a platinum vs. platinum-13% rhodium thermocouple which had a junction of 0.010 inches in diameter.

The last step before actual flame temperatures were taken was the determination of what areas of the flat flame should be sampled. In taking sample temperature measurements if the junction got any closer than 1/16 inch from the matrix the results were erroneous. This was mainly due to the fact that with the equipment used, the probe could not be kept vibration free and level enough to obtain flame temperatures this close to the matrix. This, of course, made it very difficult to obtain any information on the preignition zone of the flame. At the other end of the flame measurements were taken as far away as 2.0 inches from the matrix. Beyond this point the turbulence became too excessive to obtain any usable results.

After the preliminary work discussed above was completed, the system was considered ready for taking flame temperature measurements using the set-up shown in Figure 3. The first step was taken by adjusting the gain controls of the X-Y plotter (Figure 3, item 8) to produce an appropriate size trace. When this was accomplished, after several trial runs, the control knobs on the plotter were locked into position.

Calibration of the X-Y plotter followed by providing external known voltages from the millivolt potentiometer. As the magnitude of these voltages were recorded on the plotter they provided a standard from which to compare inputs that would eventually come from the thermocouple.

Now that the X-Y plotter had been adjusted the flame was then tuned to the desired air-fuel ratio and the system and instrumentation was then allowed to warm up, and enable all the flows to stabilize.

At this time the temperature of the pyrex chimney was measured by a thermocouple which was placed on the outside of the chimney opposite the area in which the temperature probe traversed. The thermocouple was fastened to the glass chimney by using a piece of heat resistant adhesive tape. This can be seen in Figure 3, item 5. The temperatures of the chimney wall were monitored and read using the millivolt potentiometer. This temperature was used for the radiation correction on the thermocouple.

Before proceeding with temperature measurements, the probe was made to traverse the full diameter of the matrix once to record the output indicator numbers on the sweep drive unit (Figure 3, item 9) corresponding to certain relative positions on the matrix. This insured the possibility of being able to return the probe to the various positions in the flame at any time desired.

Finally, the temperature probe was driven through the

flame by the traversing mechanism motor. The millivolt output of the thermocouple and the voltage output of the sweep drive unit corresponding to position were both recorded on the X-Y plotter. This procedure was followed for different air-fuel ratios with and without the addition of nitrogen. At the same time, the chimney wall temperatures were measured using the wall thermocouple.

The flame temperature measurements were taken from the radial edge of the matrix holder to a point past the center of the matrix. In cases where the nitrogen nozzle was obstructing, the measurements were taken up to the wall of the nozzle. The temperatures were measured at heights above the matrix of 1/16", 1/8", 1/4", 3/8", 1/2", 3/4", 1", 1-1/2", 1-3/4" and 2".

After the thermocouple outputs were recorded by the X-Y plotter, it was necessary to calculate the temperature at enough points on each curve to enable the drawing of a profile of temperature vs. radial distance. This procedure will be discussed in Chapter IV.

Species Concentration Measurements

Concentration measurements of the various species had to be obtained from the same locations in the flame as the temperature measurements. The system employed to accomplish this is shown in Figure 4 of Chapter II and also described in detail in that chapter.

The following is a description of the procedures used to obtain the concentration profiles with the system developed. First, some of the equipment, such as the mass spectrometer and the gas chromatograph, were turned on to allow the systems to warm up and stabilize before meaningful measurements could be taken. At the same time the micro-metering needle valve, (Figure 4, item 6), was adjusted so that the vacuum thermistor gage meter, (Figure 4, item 7), read 750 μ. The micro-metering needle T-valve (Figure 4, item 10), was set on .500 and the micro-metering needle valve, (Figure 4, item 9), was opened to obtain a pressure of 4×10^{-6} torr on the mass spectrometer. After several hours of warm up the next step was to set the height and position of the probe by using the assembly shown in Figure 1 and described in Chapter II. This was critical because the sampling points had to match the positions where the temperatures were taken. Once the assembly was locked into position the probe was made to traverse the matrix several times to ensure that it stayed level and traversed the desired path. After the selection of the desired air-fuel ratio, the gases were then turned on and adjusted accordingly. The flame was then ignited and the system allowed to stabilize. Next, the X-Y plotter control knobs were locked into place after a few sample runs indicated the desired amplification. The partial pressure readings on the mass spectrometer were adjusted to zero ahead of time for each species to be measured. With all systems ready the mass

spectrometer was set to monitor the mass of a desired species and the probe was then made to traverse the flame. The output signals of the mass spectrometer and the sweep drive unit were recorded on the X-Y plotter. The procedure just described was carried out twice for each species sampled, once without N_2 injection and once with N_2 injection in the flat flame. As the particular species concentration reached different levels the reading on the mass spectrometer (Figure 4, item 8) was manually recorded on the X-Y plotter graph. These same steps were used for each species sampled.

Gas samples were taken at six different heights above the burner matrix. These were heights of 1/8", 1/4", 1/2", 1", 1-1/2" and 2". Each traverse started at the edge of the matrix holder and continued across the center-line of the matrix to a point beyond the geometric center. At some probing heights the traverse could only go as far as the wall of the nitrogen injection nozzle.

The species monitored by the mass spectrometer were CO_2, O_2, N_2 and H_2O. These were the main components in the gas mixture which could be separated by the available gas chromatograph columns. Very small amounts of other gases were detected by the gas chromatograph, however, no attempt was made to identify these.

In order for the mass spectrometer to produce any meaningful results a calibration had to be performed. This was needed to give the values displayed on the scope of the

mass spectrometer a quantitative measure.

The calibration of H_2O vapor was carried out using two sources of air samples. The first source was the air in the room. At this time the mass spectrometer was set up to read H_2O. When the air sample was received by the mass spectrometer the reading was recorded. Simultaneously, the room dry bulb and wet bulb temperatures were measured. Using this information the room air relative humidity and the vapor pressure can be evaluated. This will be shown in the next chapter.

The second air sample source was a saturation bottle where the air was bubbled through distilled water and then sampled by the mass spectrometer. The temperature of the saturated air was measured and the vapor pressure can be determined from steam tables.

The remaining three species (N_2, O_2 and CO_2) were calibrated using the gas chromatograph. To calibrate the N_2, first pure N_2 gas was sampled by the gas chromatograph and after a number of trials, the area of 100% N_2 was determined by the area integrator on the strip chart recorder (Figure 4, item 1). Next the flame was ignited and a sample was taken for analysis by the gas chromatograph while the mass spectrometer was set for N_2. After several trials an average area of the gas chromatograph readout was developed. By knowing this and the corrected barometric pressure, the partial pressure of N_2 could be calculated. The details of

these calculations will be presented in Chapter IV.

In order to calibrate O_2 a sample of air was first received by the gas chromatograph. After several samples the average area for O_2 was determined. From this the area of a sample of pure O_2 can be calculated. Next, a sample from the flame was injected into the mass spectrometer and an average area for O_2 was established while simultaneously the reading on the mass spectrometer was recorded. Thus, the partial pressure of O_2 can be calculated.

Finally, a calibrated sample of 14.52% CO_2 in N_2 was used to calibrate the CO_2 gas. For this sample the gas chromatograph average area was developed. From this area the area of pure CO_2 can be calculated. Next, while extracting a sample from the flame the mass spectrometer reading was recorded and at the same time an average area for this reading of CO_2 was developed on the gas chromatograph. This provided the needed information to calculate the partial pressure of CO_2.

The procedures used as described above for calibrating the mass spectrometer for the various species was particularly important in that it demonstrated the combined use of both the mass spectrometer and the gas chromatograph. The development of this procedure was one of the prime concerns of this thesis.

CHAPTER IV

RESULTS AND DISCUSSION

Data Reduction

The data obtained in the experimental studies presented here can be divided into three main categories:

1. Flow measurements,
2. Temperature measurements, and
3. Concentration measurements.

The calculations and methods used to reduce the data for the above categories are discussed in the sections which follow.

Flow Measurements

The first step in the procedures used for data reduction was the calculation of the volumetric and mass flow rates of the gases employed for this study. This was accomplished through the combined use of the flowmeter calibration curves included in Appendix A and a program written for the Wang 720 calculator. A detailed presentation of sample calculations have been included in Appendix B. Typical results of such calculations are shown in Table 1.

Temperature Measurements

The temperature profiles were produced with the instrumentation shown in Figure 3. For every change in

Table 1. Volumetric and Mass Flow Rates for Various Air-Fuel Ratios

FLAT FLAME BURNER WITH AN OPPOSED INERT GAS JET

Date: 5/1/1973

Data Sheet No.	$\dot{V}_{air}$ ft^3/hr	$\dot{m}_{air}$ lb_m/hr	$\dot{V}_{CH4}$ ft^3/hr	$\dot{m}_{CH4}$ lb_m/hr	A/F	Φ	$\dot{V}_{N2}$ ft^3/hr	$\dot{m}_{N2}$ lb_m/hr
60	30.51	2.208	2.963	.1168	18.90	.9060	2.727	.2001
61	53.31	4.096	5.417	.2146	19.08	.8974	8.773	1.2705
62	60.61	4.826	4.579	.1824	26.45	.6475	8.729	1.2770
63	38.69	2.869	2.720	.1079	26.58	.6443	2.721	.2006
64	30.51	2.208	2.963	.1168	18.90	.9061	2.728	.2001
65	38.83	2.858	2.729	.1075	26.57	.6446	2.728	.2001
66	53.26	4.100	5.415	.2147	19.09	.8970	8.719	1.2785
67	60.82	4.810	4.596	.1817	26.46	.6473	8.714	1.2791
68	30.47	2.211	2.958	.1170	18.90	.9062	2.723	.2004
69	38.78	2.862	2.725	.1077	26.56	.6447	2.723	.2004
70	53.29	4.097	5.407	.2150	19.05	.8988	8.762	1.2721
71	60.67	4.822	4.589	.1820	26.48	.6467	8.730	1.2768

either the flow rate or the height at which a gas sample was taken, two temperature profiles were made. One temperature profile was made with N_2 injection and one without N_2 injection. A representative sample of the thermocouple output record is shown in Figure 6. A summary of all the temperature measurements carried out during the present study is given in Table 2. Only the test results designated with circled x's have been included in this thesis.

As noted in Figure 6, the recorded output of the thermocouple was in mv consequently, the next step was to pick average points along the curves and to calculate the corresponding temperature of these points. A multiplying factor was established for the vertical scale of the curves through the use of a standard mv potentiometer source. With this multiplying factor and the conversion tables found in The Omega Temperature Measurement Handbook, the temperature for each particular point could be established.

The temperature found at each average point on the profile, however, had to be corrected for thermal radiation. This was accomplished through the use of a procedure specified in Reference [6] and a program for the Wang 720 calculator. To use the program the following information was needed and used: E = thermocouple emissivity, e = gas emissivity, d = diameter of the thermocouple bead, area of gas flow, $\dot{m}_{air}$ = lb_m/hr of air, $\dot{m}_{CH4}$ = lb_m/hr of CH_4, $\dot{m}_{N2}$ = lb_m/hr of N_2, t_c = temperature of the thermocouple,

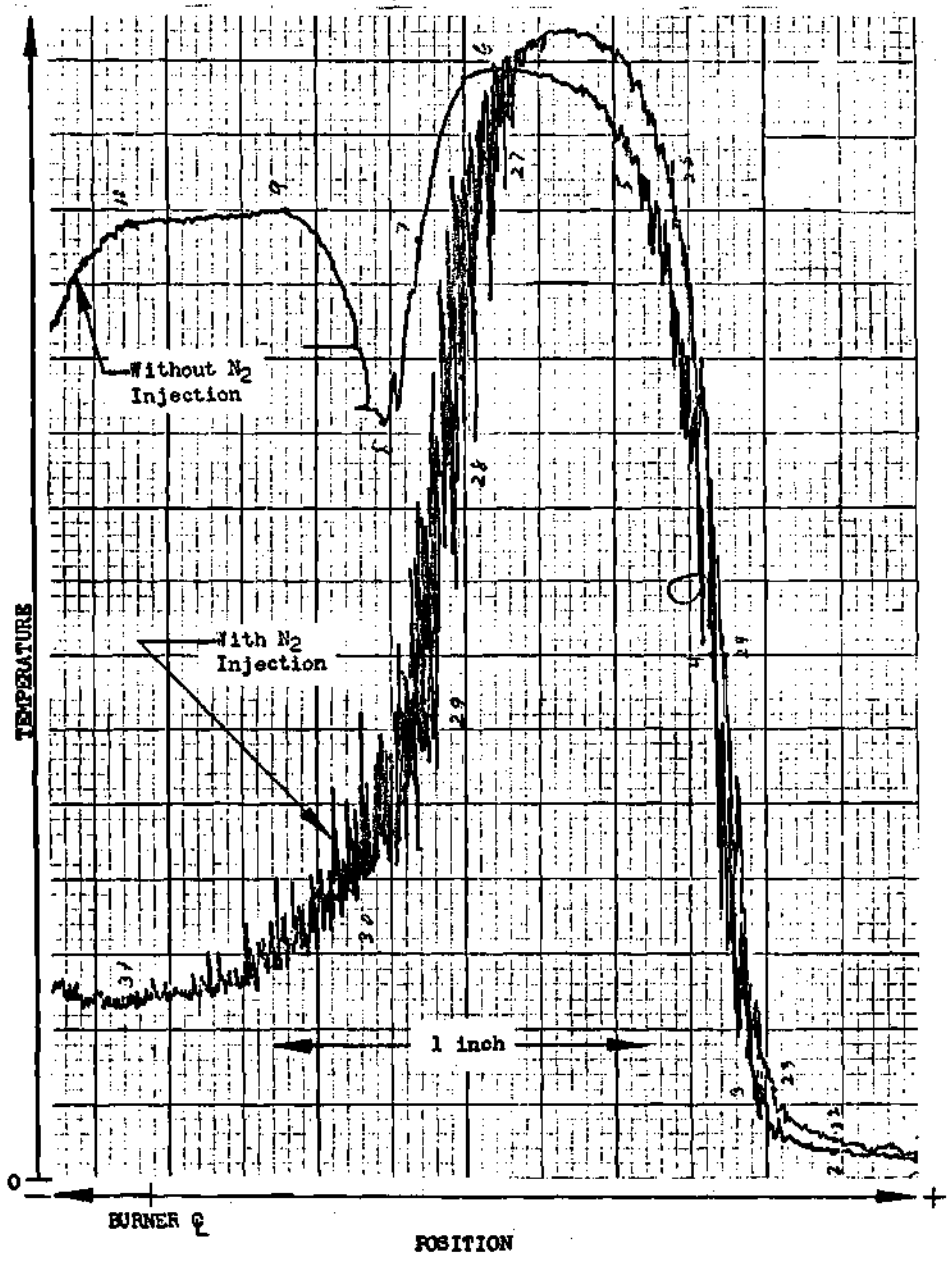

Figure 6. Representative Thermocouple Outputs Traversing Through Reaction Zone, With and Without N_2 Injection; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = .217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = .899; Sample Taken 0.50 Inches Above Burner; Numbers on the Curve Represent Points Where the Actual Temperature was Calculated

Table 2. Summary of Temperature Measurements

Φ	$\dot{m}_{mix}$ lb_m/hr	Height Above Burner (inches)									
		$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{3}{4}$	1	$1\frac{1}{2}$	$1\frac{3}{4}$	2
.65	5.03	X	⊗	X	X	X	X	⊗A	X	X	X
.65	3.00	X	⊗A	X	⊗	X	⊗A	X	⊗A	X	⊗A
.90	4.30	X	X	⊗A	X	X	⊗	X	X	X	X
.90	2.35	X	X	X	X	⊗A	X	X	⊗	X	X

Note: Temperature profiles for each of the above were obtained both with N_2 injection and without N_2 injection. Nitrogen flow rates of 0.20 and 1.28 lb_m/hr were used for the low and high combustible mixture flow rates, respectively. Circled X's represent results which have been included in this thesis. The letter A designates those which are placed in Appendix C.

t_w = temperature of the chimney wall, P_b = barometric pressure, and N which is obtained from a graph where the mean temperature, t_m, is plotted using N as the vertical axis and Vd, product of the gas velocity and diameter of the thermocouple, as the horizontal axis [6]. Another computer program calculated $\dot{m}_{air}$, $\dot{m}_{CH4}$ and $\dot{m}_{N2}$ as discussed earlier. Sample calculations of these are shown in Appendix B. A sample of the calculator printout is included in Table 3. Once the corrected temperatures of the various points have been evaluated and corrected they were used to plot the temperature profiles. These will be presented and discussed in the results and discussion section of this thesis, which follows.

Concentration Measurements

The representative species concentration profiles produced through the use of the instrumentation shown in Figure 4 and the X-Y plotter are shown in Figures 7 through 11. The numbers with arrows pointing to specific points along the curve are the readings displayed by the mass spectrometer. These readings were then transformed into actual partial pressures by the calibration of selected points and then interpolating for the points in between, assuming a linear relationship. A summary of all the profiles obtained is presented in Table 4.

The calibration of the H_2O vapor profiles, as previously discussed, was carried out using two methods. For one method

Table 3. Thermocouple Radiation Corrections

FLAT FLAME BURNER

Thermocouple Radiation Correction

Date: 5/20/1973

E = .05 e = .10 d = .010 in Exp. No. 90 Area = .0481 ft^2

Point No.	$\dot{V}_{total}$ ft^3/s	V ft/s	V x d ft-in/s	t_c °C	t_c °F	t_w °F	t_m °F	N	t_g °F	t_g °C
1	.01822	.378	.00378	38	100	232	166	9	100	38
2	.01934	.402	.00402	57	135	232	184	10	134	57
3	.02590	.538	.00538	169	336	232	284	14	337	169
4	.05829	1.212	.01212	722	1332	232	782	42	1352	733
5	.08706	1.810	.01810	1213	2215	232	1224	81	2287	1253
6	.09321	1.937	.01937	1318	2404	232	1318	95	2496	1369
7	.08366	1.739	.01739	1155	2111	232	1172	79	2177	1192
8	.07306	1.518	.01518	974	1785	232	1009	60	1827	997
9	.08536	1.774	.01774	1184	2163	232	1198	80	2232	1222
10	.08460	1.758	.01758	1171	2140	232	1186	78	2206	1208
11	.07587	1.577	.01577	1022	1872	232	1052	65	1919	1048

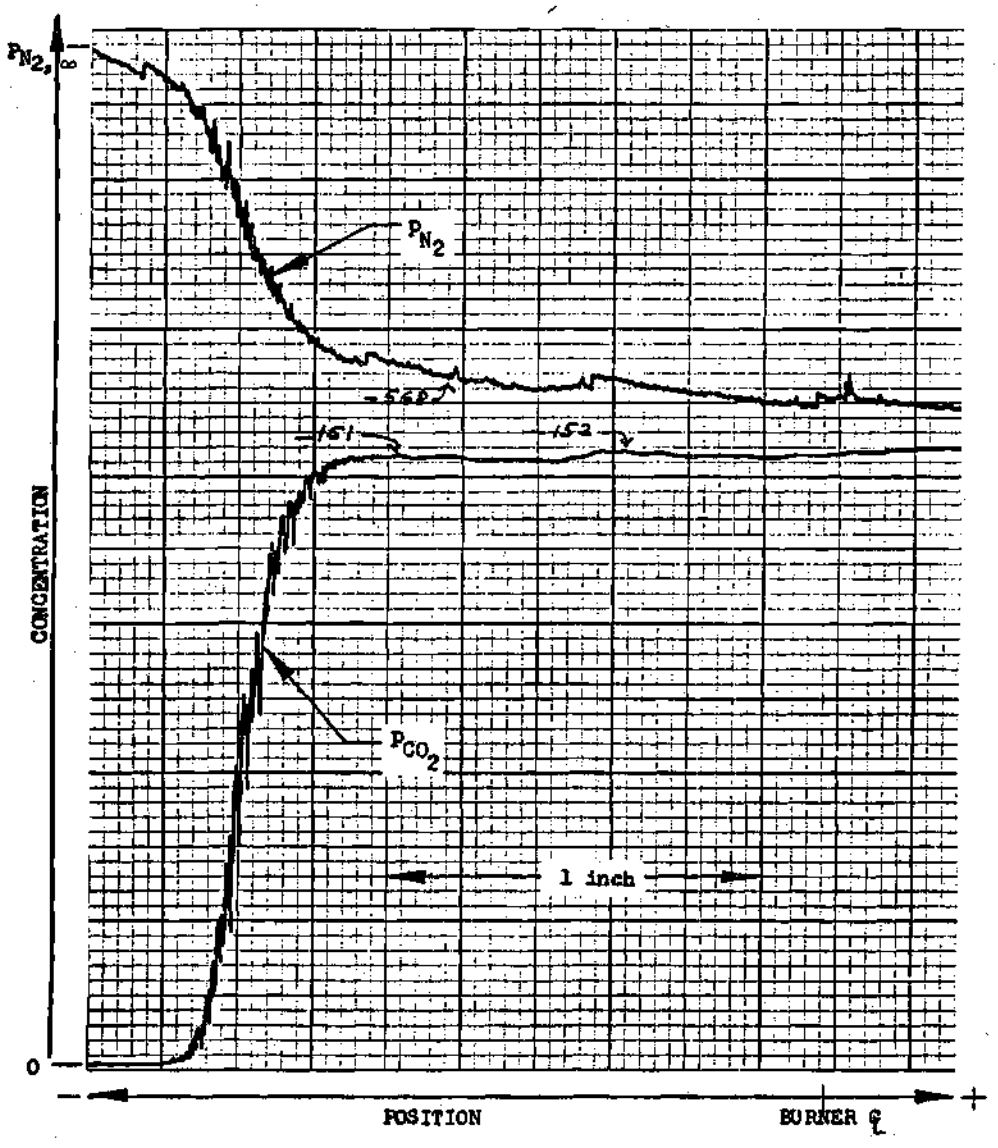

Figure 7. Representative Concentration Profiles of CO_2 and N_2 Without N_2 Injection; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = .217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = .899; Sample Taken 0.50 Inches Above Burner; Numbers on the Curves Have Been Recorded from the Output Display of the Mass Spectrometer

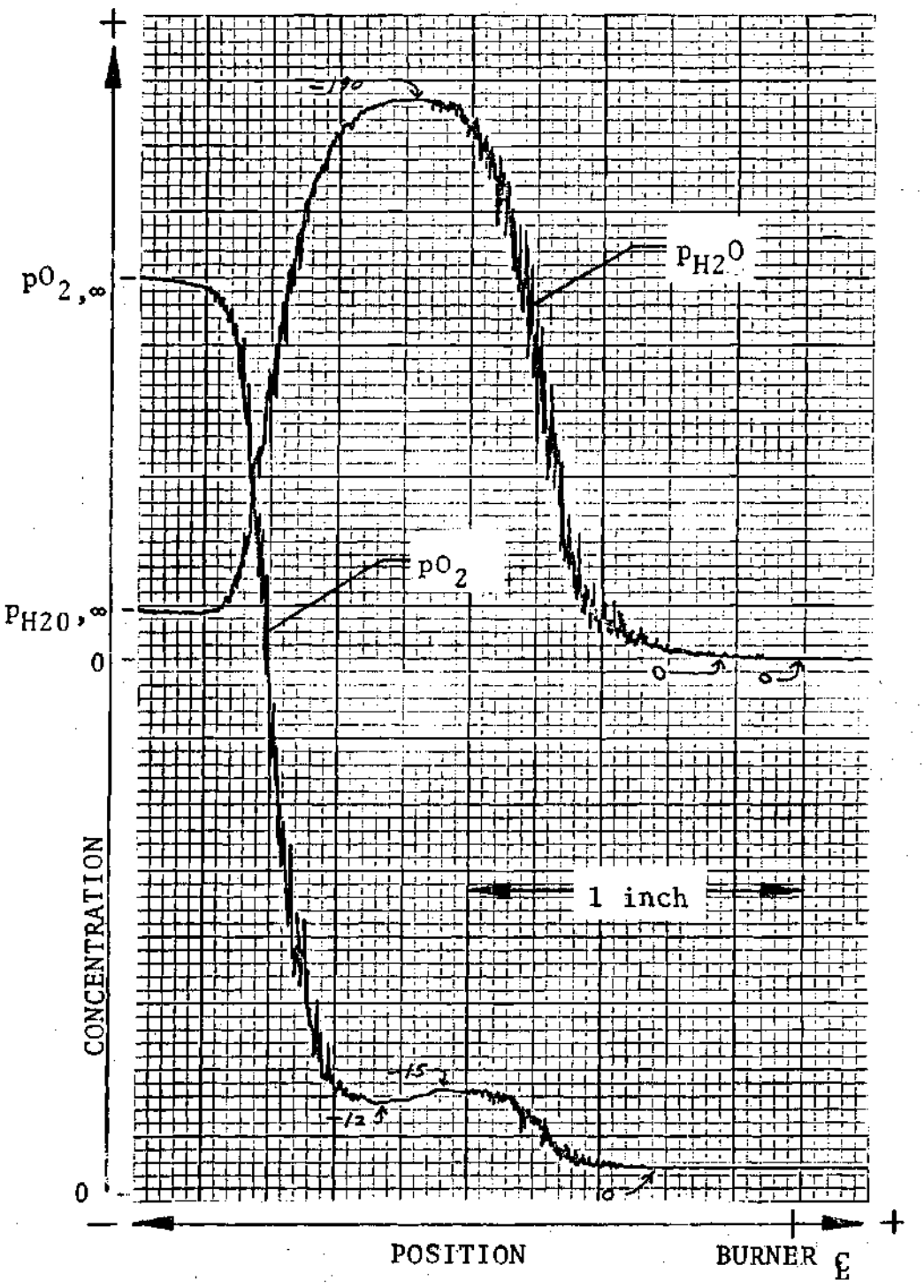

Figure 8. Representative Concentration Profiles of H_2O and O_2 with N_2 Injection; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = .217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = .899; Sample Taken 0.50 inches Above Burner; Numbers on the Curves have been Recorded from the Output Display of the Mass Spectrometer.

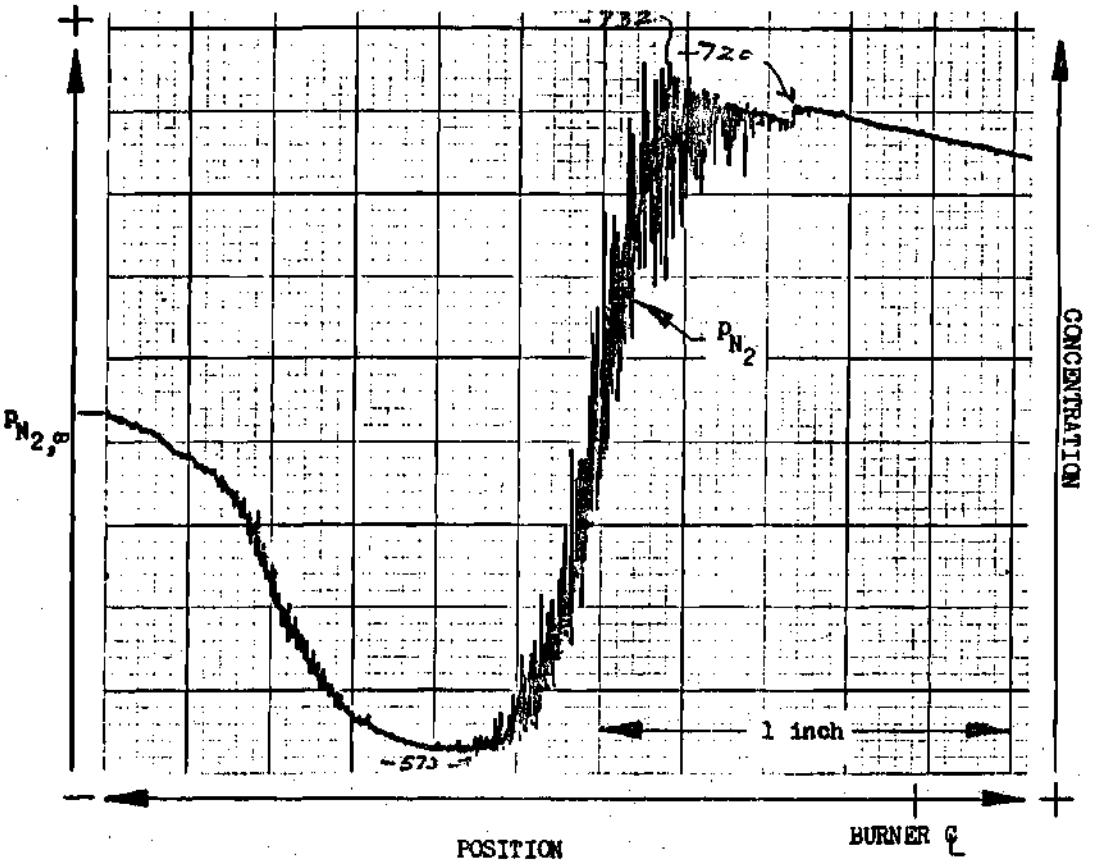

Figure 9. Representative Concentration Profile of N_2 with N_2 Injection; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = .217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = .899; Sample Taken 0.50 Inches Above Burner; Numbers on the Curves have been Recorded from the Output Display of the Mass Spectrometer

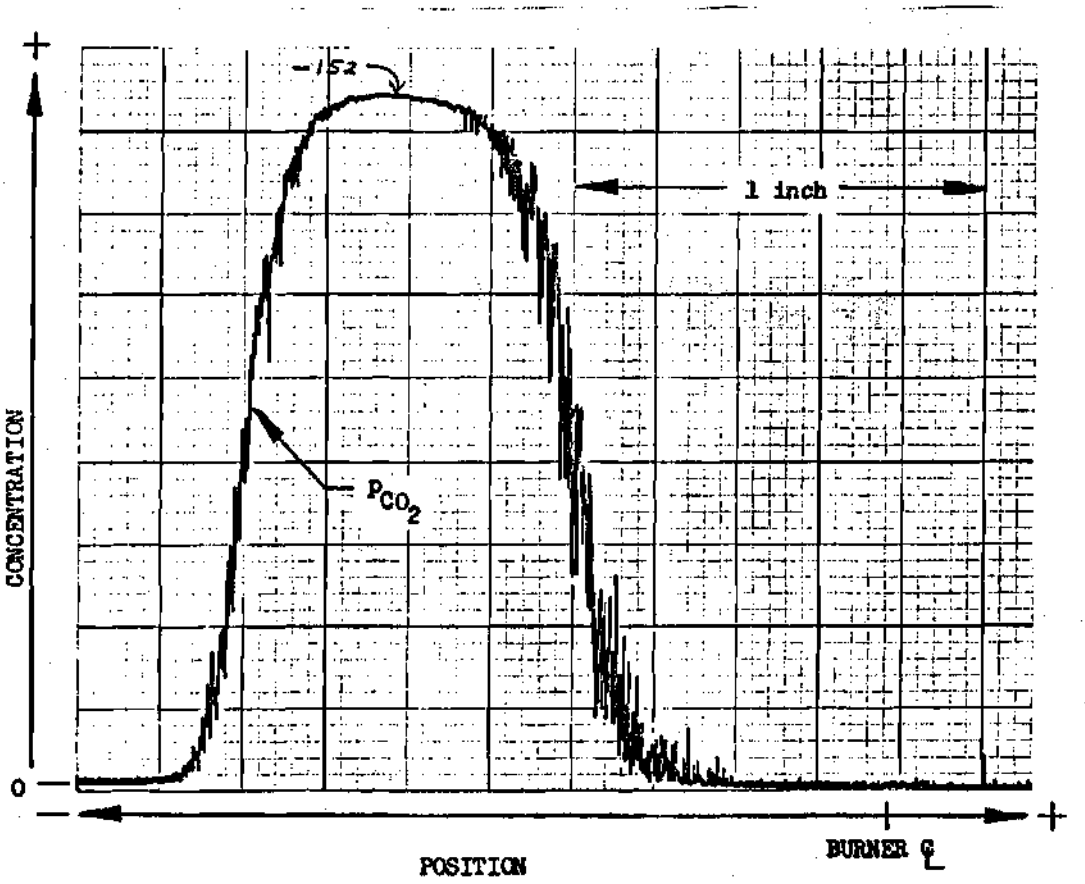

Figure 10. Representative Concentration Profile of CO_2 with N_2 Injection; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = .217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = .899; Sample Taken 0.50 Inches Above Burner; Numbers on the Curves have been Recorded from the Output Display of the Mass Spectrometer

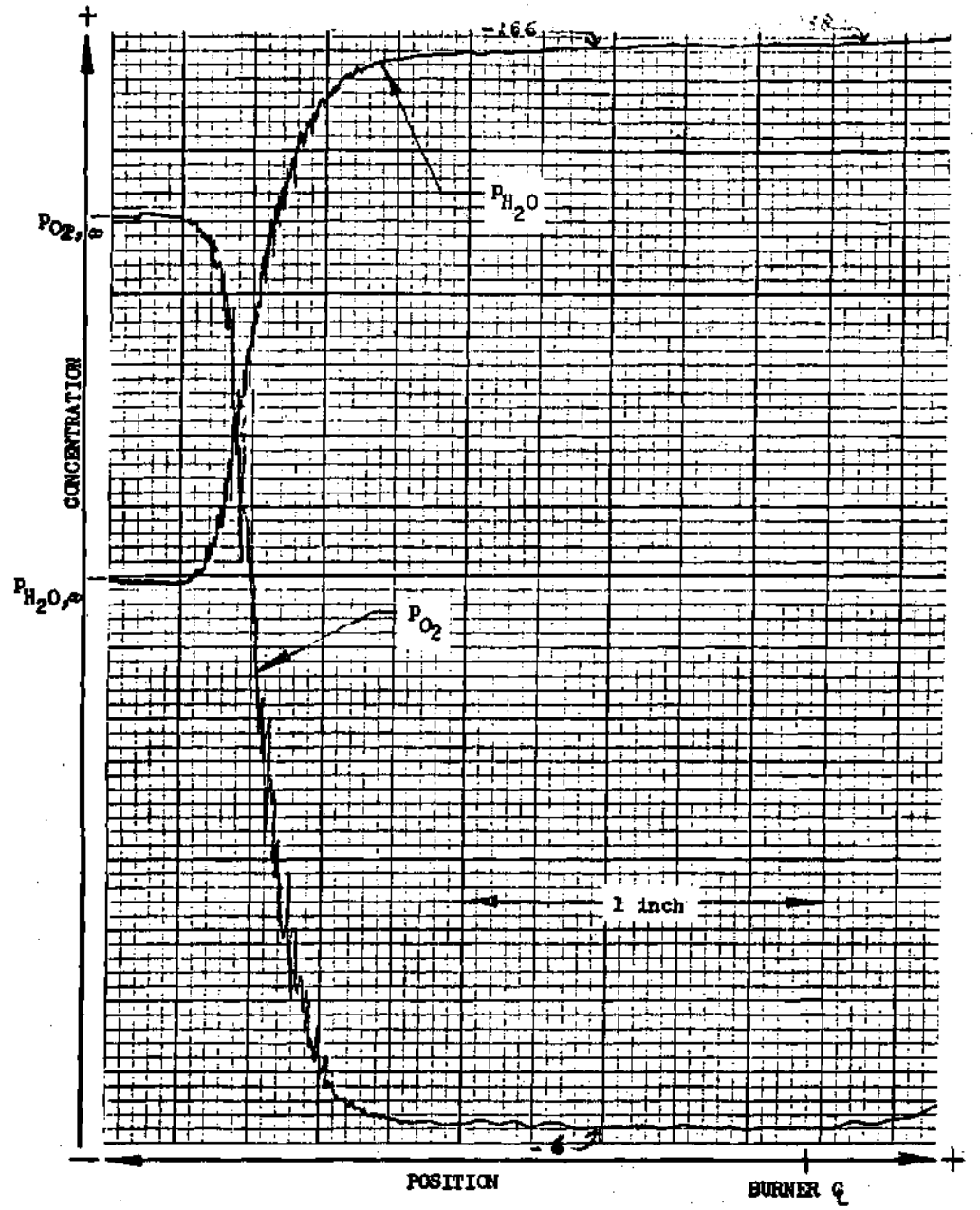

Figure 11. Representative Concentration Profiles of H_2O and O_2 without N_2 Injection; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = .217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = .899; Sample Taken 0.50 Inches Above Burner; Numbers on the Curves have been Recorded from the Output Display of the Mass Spectrometer

Table 4. Summary of Concentration Measurements for CO_2, O_2, N_2 and H_2O

Φ	$\dot{m}_{mix}$ lb_m/hr	Height Above Burner (inches)					
		$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$1\frac{1}{2}$	2
.65	5.03	X	X	X	X	⊗	X
.65	3.00	X	X	⊗ A	X	X	X
.90	4.30	⊗ A	⊗	X	⊗ A	X	⊗ A
.90	2.35	⊗	X	X	X	X	X

Note: Concentration profiles for each of the four species at each of the conditions specified above were obtained both with N_2 injection and without N_2 injection. Nitrogen flow rates of 1.28 and 0.20 lb_m/hr were used for the high and low combustible mixture flow rates, respectively. Circled X's represent results which have been included in this thesis. The letter A designates those which are placed in Appendix D.

the mass spectrometer displayed a reading of 13 while sampling room air at the temperature of 72°F and a relative humidity of 55%. By using the formula $\phi = (\frac{p_v}{p_{v,sat}})_T$, where ϕ is the relative humidity, and by obtaining $p_{v,sat}$ from the steam tables, p_v could then be evaluated in the following manner:

$$0.55 = (\frac{p_v}{0.39})_{72°F}$$

$$p_v = 0.21 \text{ psia}$$

which corresponds to the reading of 13 on the mass spectrometer.

In the second method air was bubbled through distilled water and then sampled by the mass spectrometer. This produced a reading on the mass spectrometer of 27 to 29. Since the temperature of the saturated air was 74°F the steam tables indicated $p_v = .4153$ psia. For both calibration methods the corrected barometric pressure was 29.03 in Hg. The H_2O was not calibrated by means of the gas chromatograph because of the type of column being used. However, the remaining species were calibrated with the use of this instrument.

In calibrating N_2 it was established through a number of trials that a 1 cc sample of pure N_2 through the chromatograph produced an average area on the area integrator of about 92800 units. After igniting the flame and abstracting

numerous samples when the mass spectrometer read 650 on its display, an average area of 68050 units was established. The corrected barometric pressure was 28.98 in Hg. Using the formulas:

$$V_n = \frac{V_n^c A_n}{A_n^c} \qquad \text{and} \qquad p_n = \frac{V_n p}{V_n^c}$$

and substituting in the values:

$$p_{N2} = \frac{(\frac{68050}{92800})(28.98)}{1} = 21.2 \text{ in Hg}$$

which corresponds to the 650 reading on the mass spectrometer display.

In calibrating O_2 first a sample of air was drawn by the gas chromatograph producing an average area of 18125 units. Since O_2 comprises 20.99% of air, by dividing 18125 by 20.99% it can be reasonably said that a 1 cc sample of pure O_2 would have an area of 86500 units. Next, by using the flame and the mass spectrometer it was seen that the average area when O_2 produced a reading of 190 was 17400 units. Again, using the above formulas established p_{O2} = 5.83 in Hg.

In calibrating the CO_2 gas a sample of 14.52% CO_2 in N_2 was used. For this sample the gas chromatograph showed an average area of 19800 units. Thus, a 1 cc pure sample of CO_2 would have an area of about 136300 units. Next, a sample

was taken from the flame when the mass spectrometer read 108 for CO_2. This produced an average area by the gas chromatograph of 9539 units. Again, using the above formulas it was found that p_{CO_2} = 2.02 in Hg.

It has been shown in previous trials that there is a fairly linear relationship between the reading on the mass spectrometer and the computed partial pressure for each particular species. Using this premise, concentration profiles were drawn as shown in the following section on concentration profiles.

Results and Discussion

The results of this work are presented and discussed in two groups:

(1) Temperature profiles, and

(2) Species concentration profiles

Following these two sections a discussion is presented on the performance of the equipment.

Temperature Profiles

As summarized in Table 2, the following will show temperature profiles at heights above the burner matrix of 1/8", 3/8", 3/4" and 1-1/2". These are reflected in Figures 12 through 15. The remainder of the profiles included in the thesis as designated in Table 2 may be seen in Figures 31 through 38 in Appendix C.

Figure 12 and 13 indicate that the injection of N_2

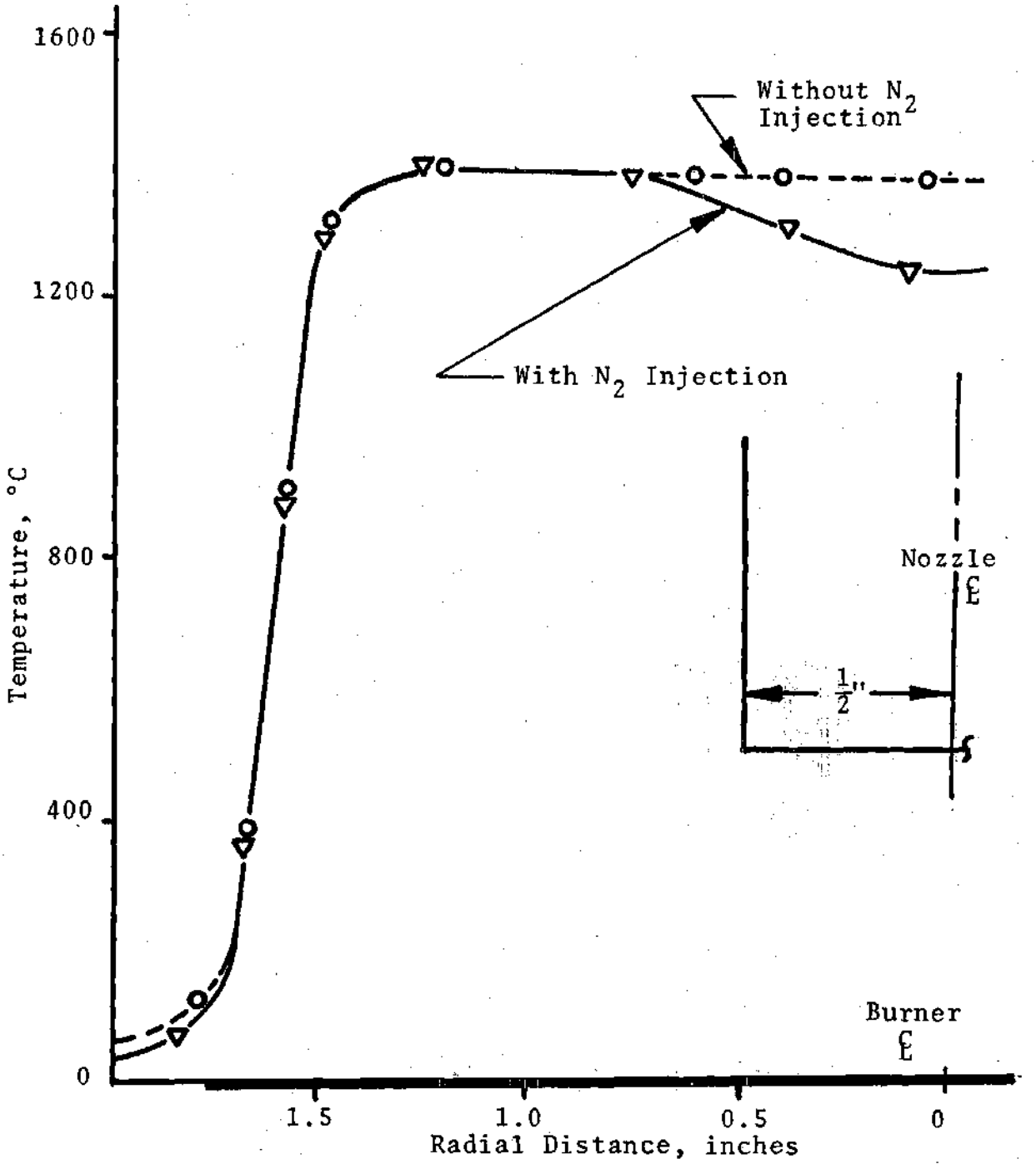

Figure 12. Flame Temperature Profiles; Air Flow Rate = 4.852 lb_m/hr, CH_4 Flow Rate = 0.184 lb_m/hr, N_2 Flow Rate = 1.280 lb_m/hr, Φ = 0.648, Sample Taken 1/8 Inches Above Burner

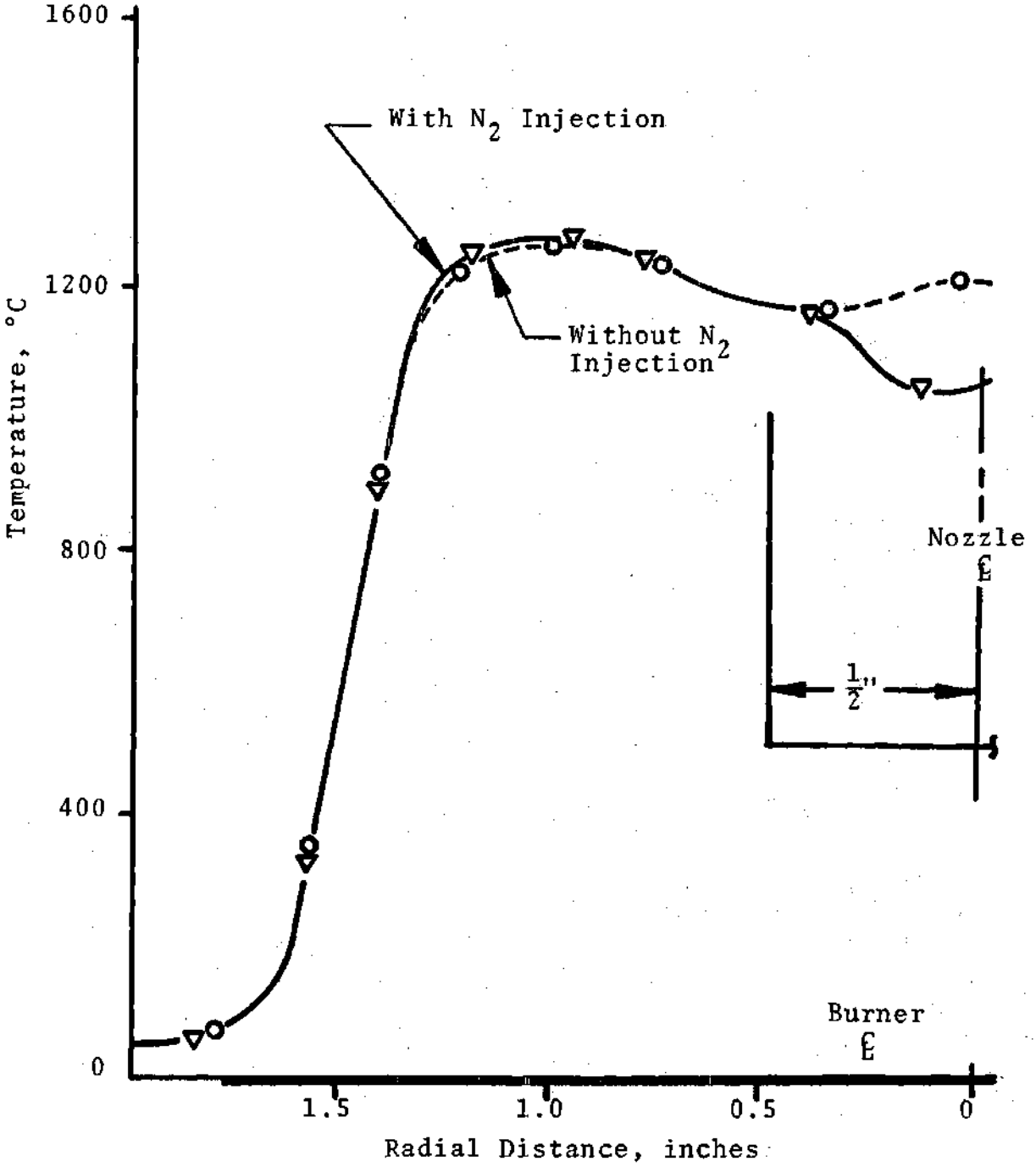

Figure 13. Flame Temperature Profiles; Air Flow Rate = 2.888 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.644, Sample Taken 3/8 Inches Above Burner

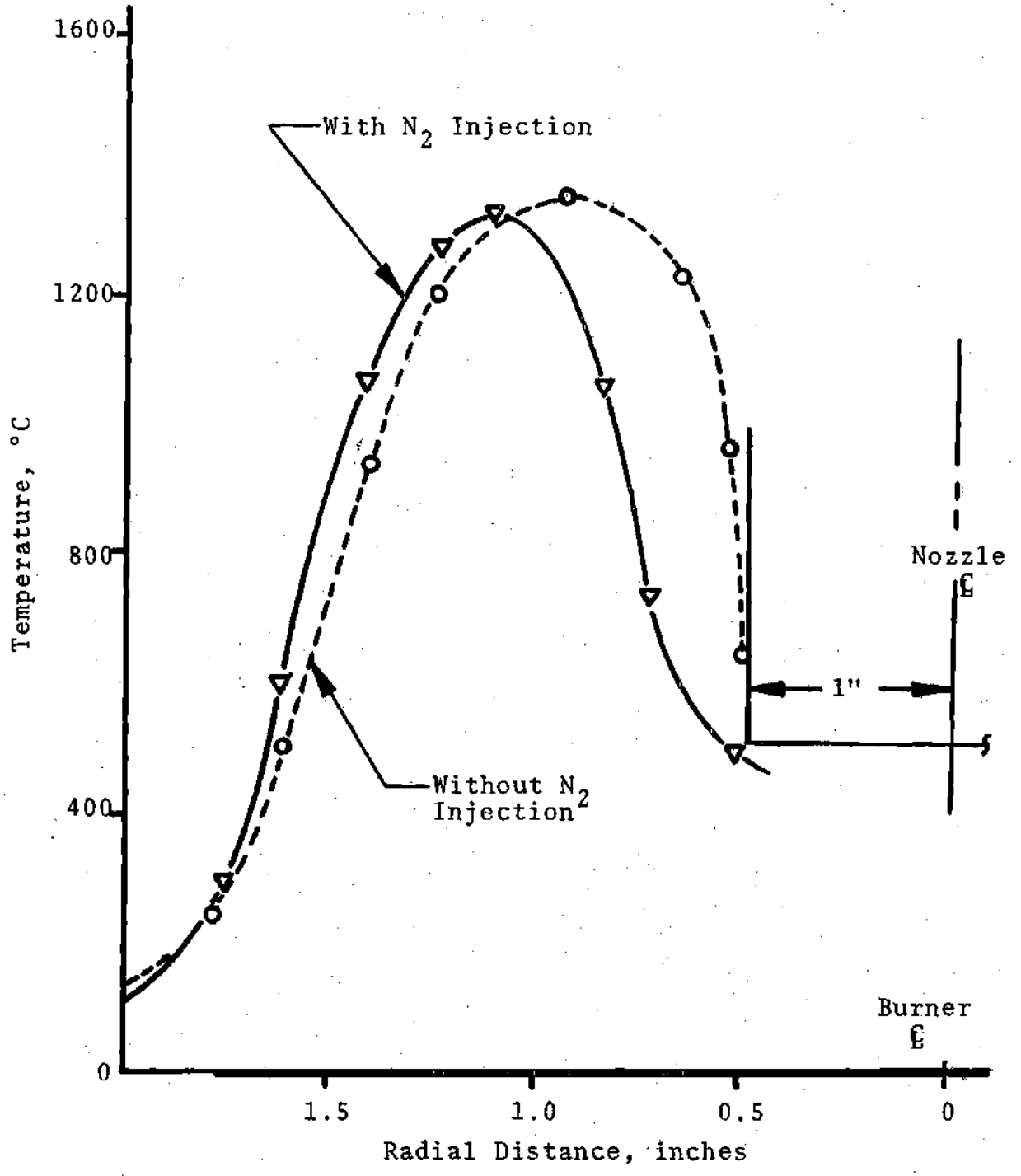

Figure 14. Flame Temperature Profiles; Air Flow Rate = 4.097 lb_m/hr, CH_4 Flow Rate = 0.215 lb_m/hr, N_2 Flow Rate = 1.272 lb_m/hr, Φ = 0.899, Sample Taken 3/4 Inches Above Burner

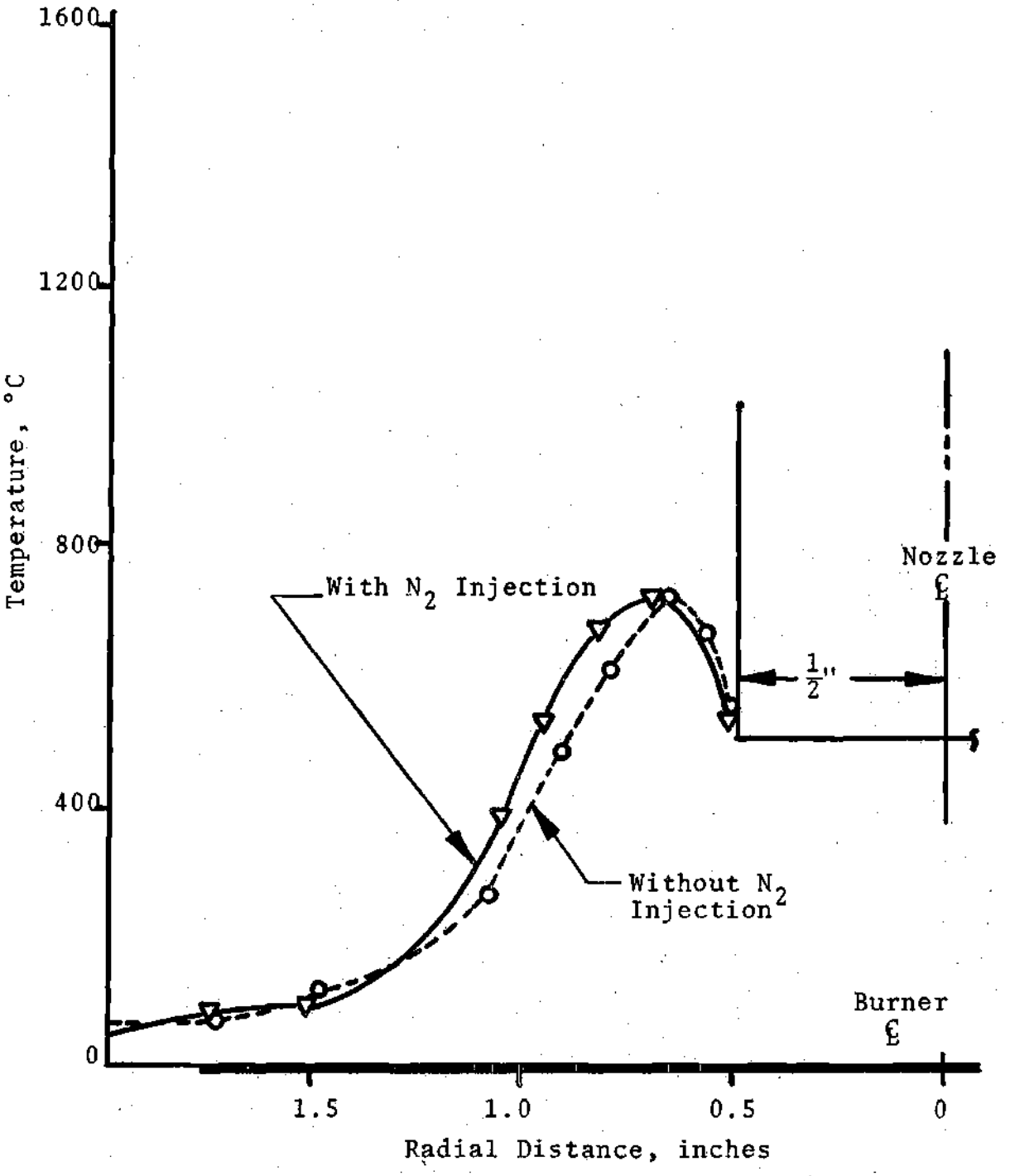

Figure 15. Flame Temperature Profiles; Air Flow Rate = 2.208 lb_m/hr, CH_4 Flow Rate = 0.117 lb_m/hr, N_2 Flow Rate = 0.200 lb_m/hr, Φ = 0.906, Sample Taken 1.50 Inches Above Burner

lowers the temperature immediately below the injection nozzle and also a certain radial distance out (about 0.8 inches) from the center of the nozzle. Beyond this point the temperature is actually higher with the injection of N_2 (see also curve in Appendix C). This occurrence is noticed at both stoichiometric ratios used. However, at the lower flow rate the temperature difference is smaller. Also, a lower stoichiometric ratio shrinks the temperature difference even further. This can be seen by studying the profiles in Appendix C.

Concentration Profiles

As summarized in Table 4, the following will show concentration profiles of CO_2, O_2, N_2 and H_2O at heights above the burner matrix of 1/8", 1/4" and 1-1/2". These are reflected in Figures 16 through 27. The remainder of the profiles included in this thesis as designated in Table 4 may be seen in Figures 39 through 58 in Appendix D.

The species sampling method used proved to be quite reliable. For each sampling run the total of the partial pressures of all the species examined added up quite close to the atmospheric pressure. This indicates that the method works and also that no major species was left out.

The quartz probe that was used worked quite well. The fact that the probe was heated eliminates, to a great degree, the possibility of the probe acting as a heat sink. Thus, the temperature and the enthalpy in the region being

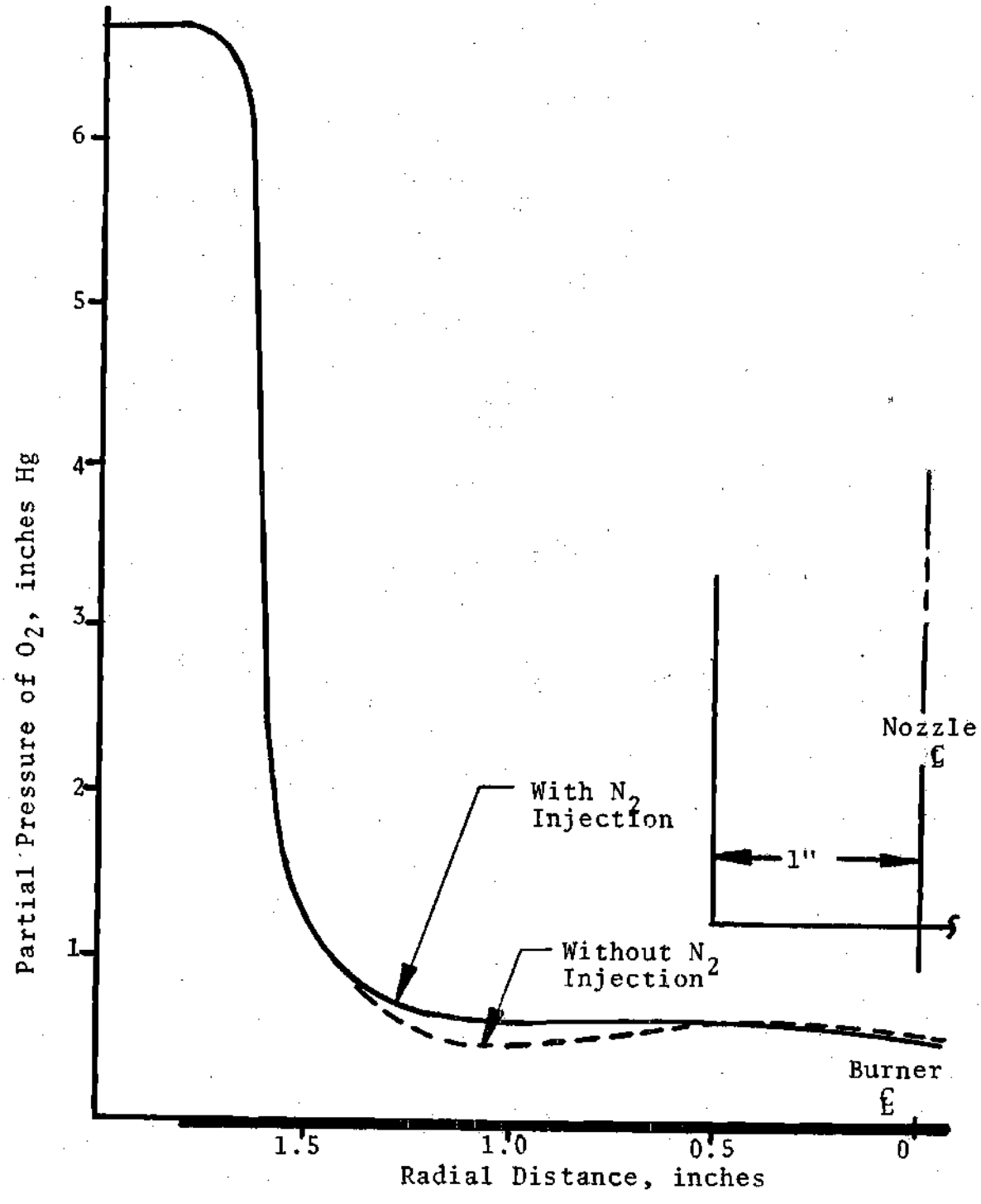

Figure 16. Concentration Profiles of O_2; Air Flow Rate = 2.227 lb_m/hr, CH_4 Flow Rate = 0.118 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.906, Sample Taken 1/8 Inch Above Burner

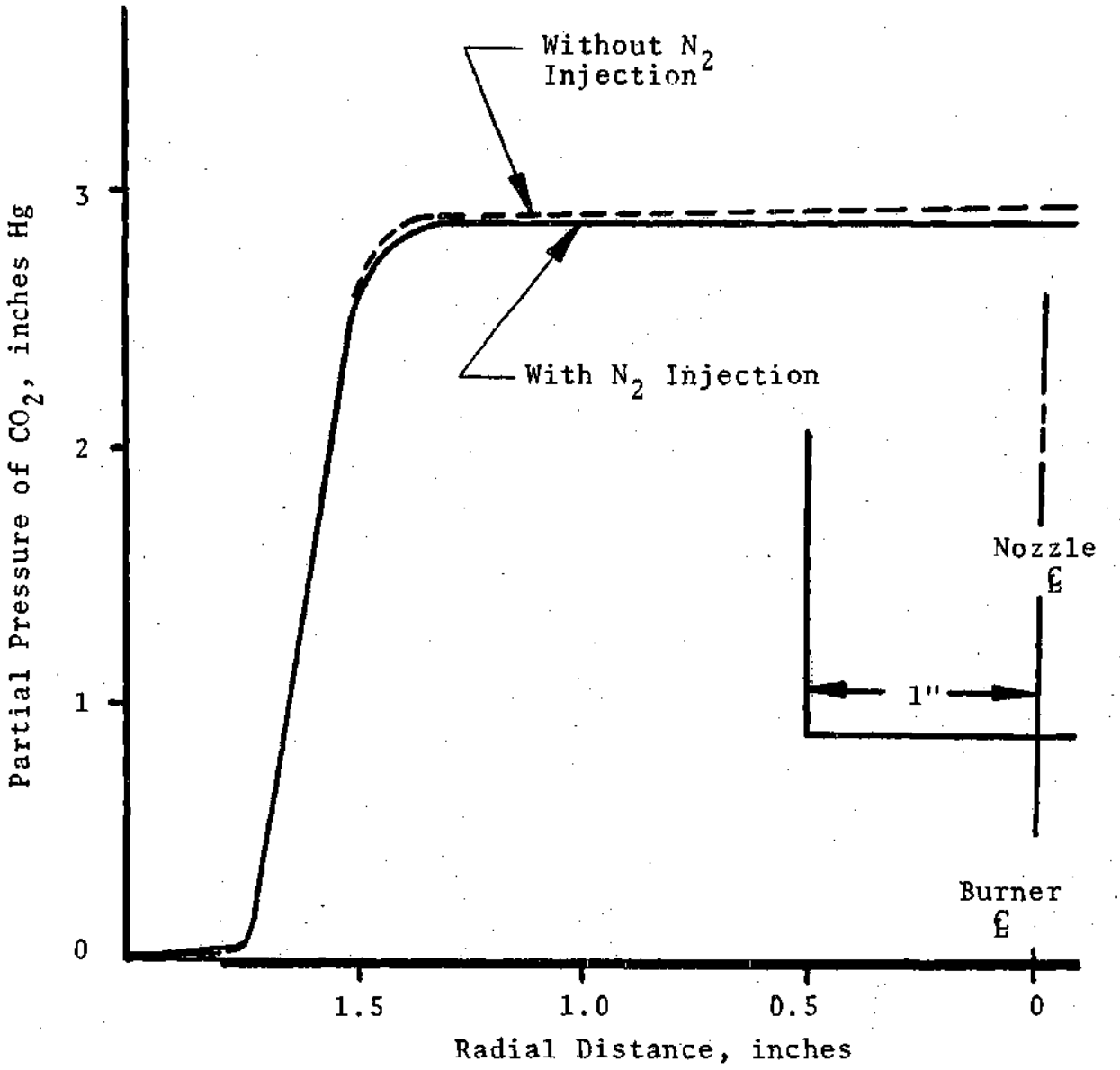

Figure 17. Concentration Profiles of CO_2; Air Flow Rate = 2.227 lb_m/hr, CH_4 Flow Rate = 0.118 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.906, Sample Taken 1/8 Inches Above Burner

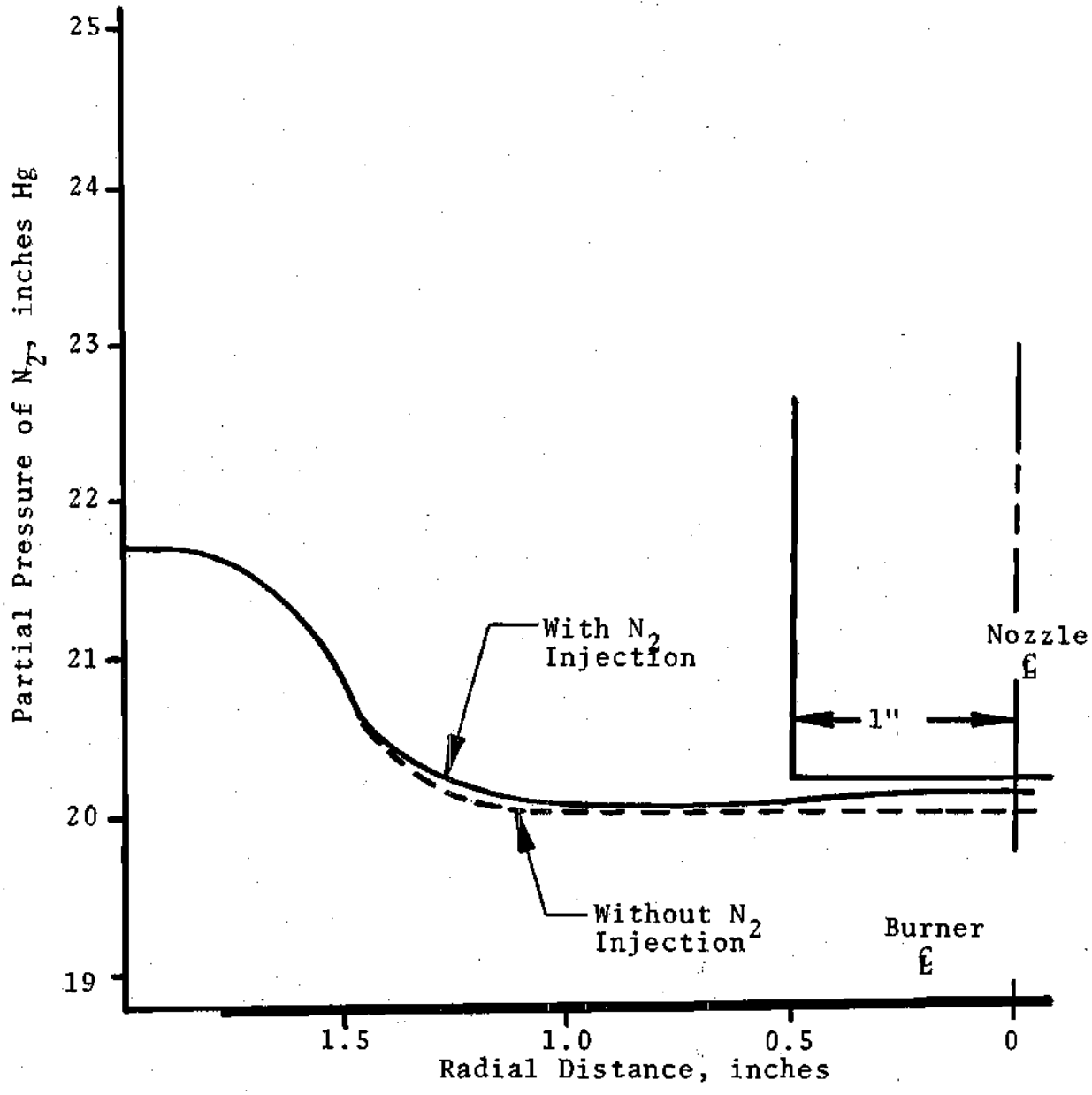

Figure 18. Concentration Profiles of N_2; Air Flow Rate = 2.227 lb_m/hr, CH_4 Flow Rate = 0.118 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.906, Sample Taken 1/8 Inch Above Burner

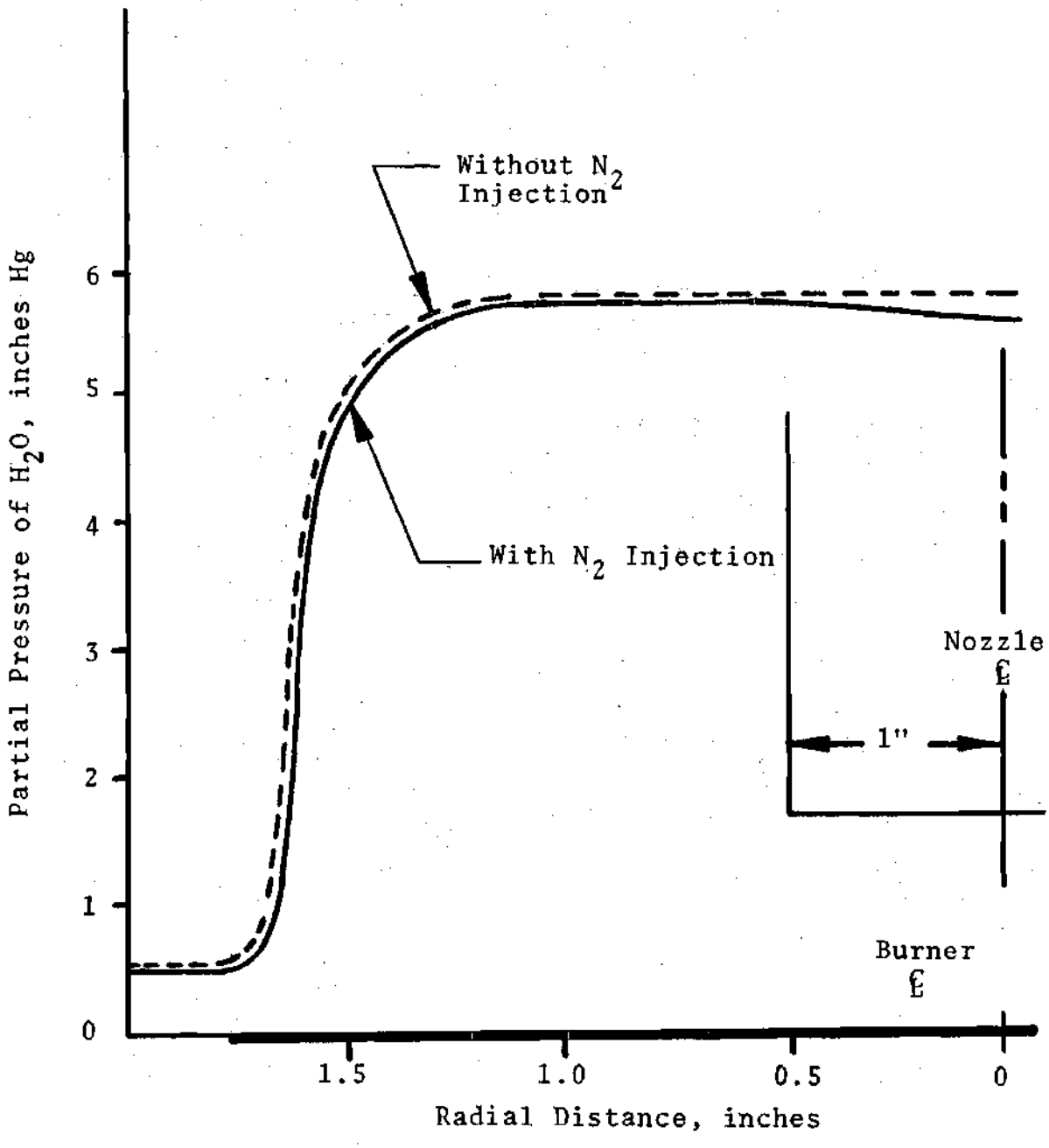

Figure 19. Concentration Profiles of H_2O; Air Flow Rate = 2.227 lb_m/hr, CH_4 Flow Rate = 0.118 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.906, Sample Taken 1/8 Inch Above Burner

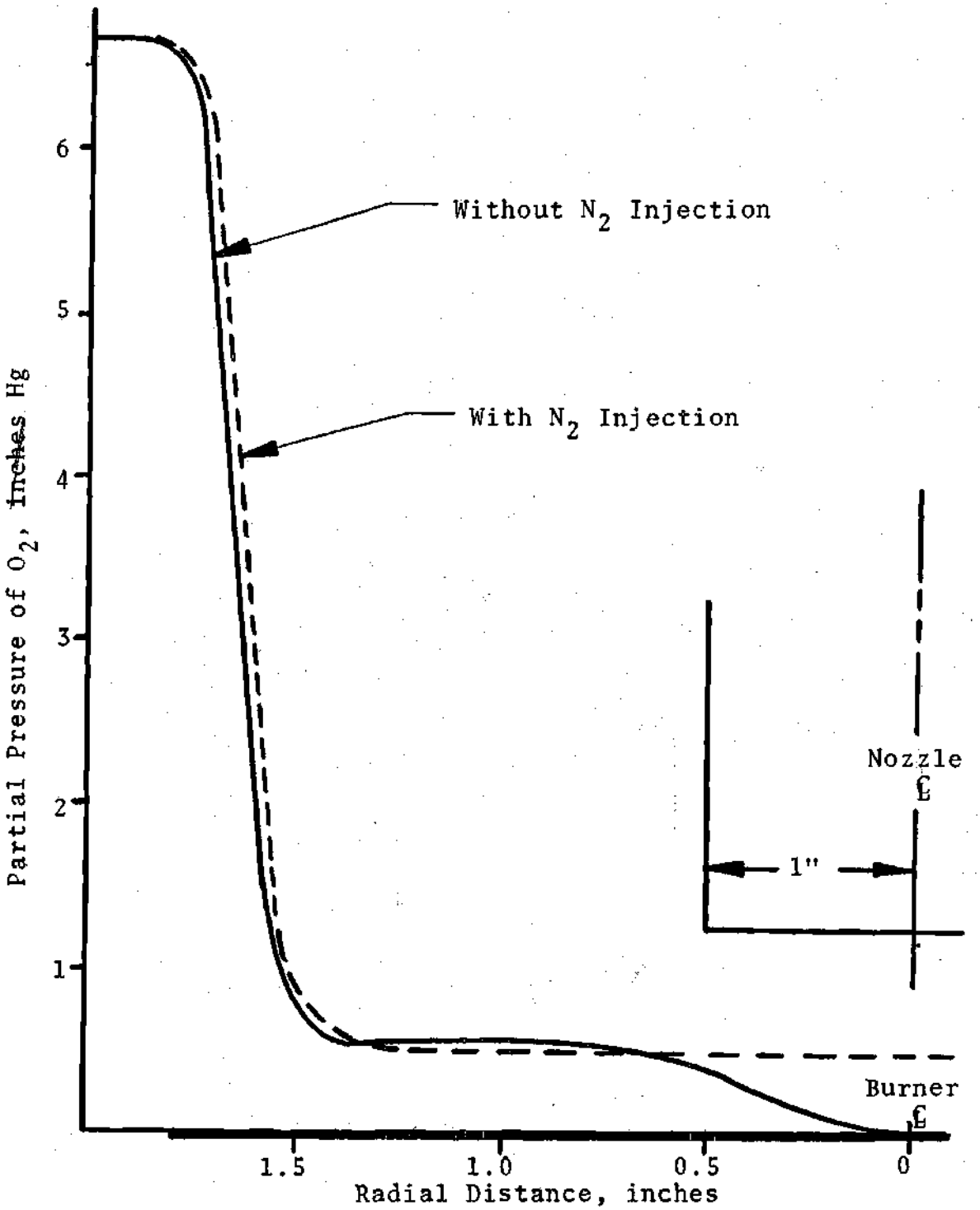

Figure 20. Concentration Profiles of O_2; Air Flow Rate = 4.142 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.276 lb_m/hr, Φ = 0.898, Sample Taken 1/4 Inch Above Burner

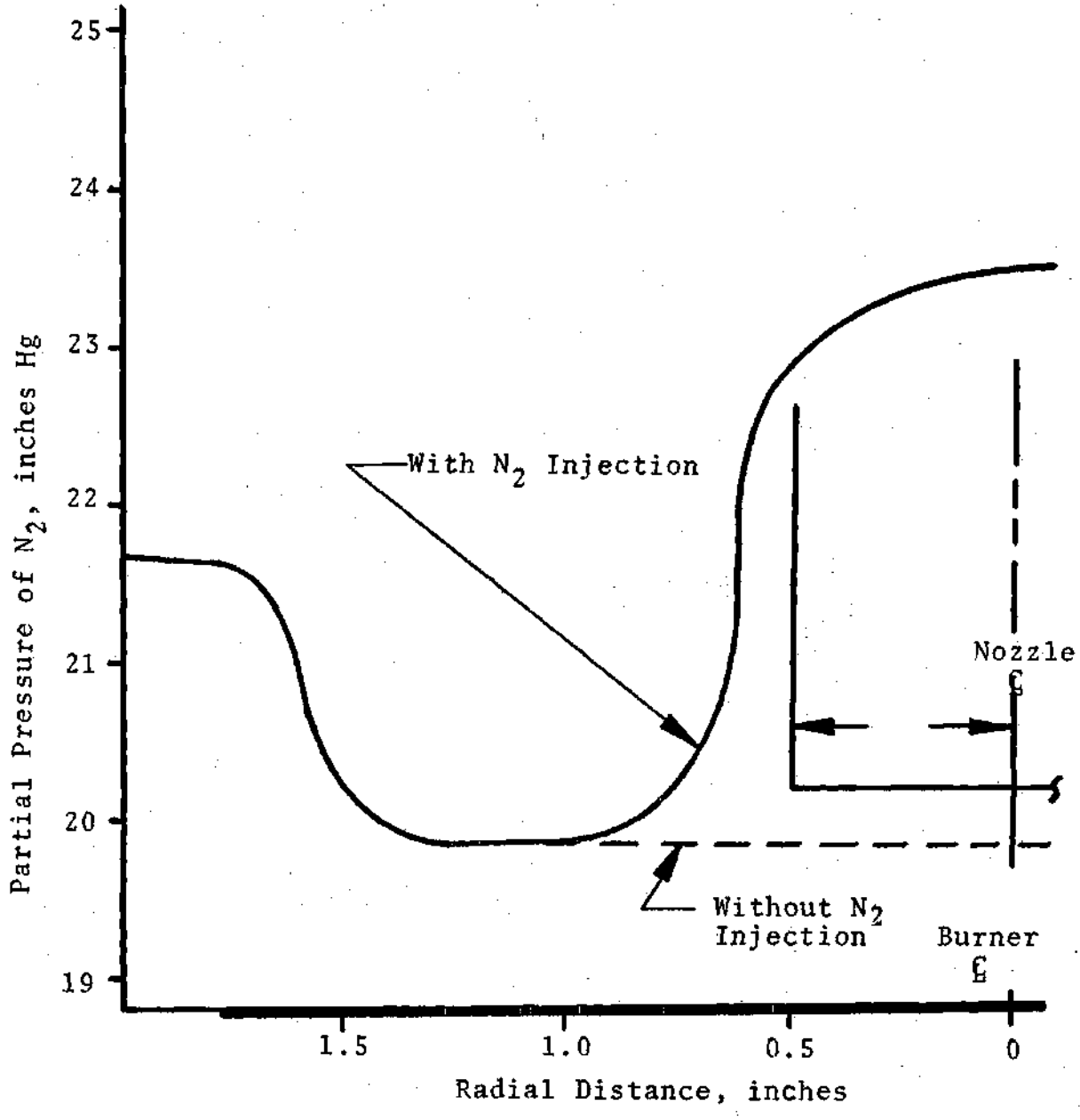

Figure 21. Concentration Profiles of N_2; Air Flow Rate = 4.142 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.276 lb_m/hr, Φ = 0.898, Sample Taken 1/4 Inch Above Burner

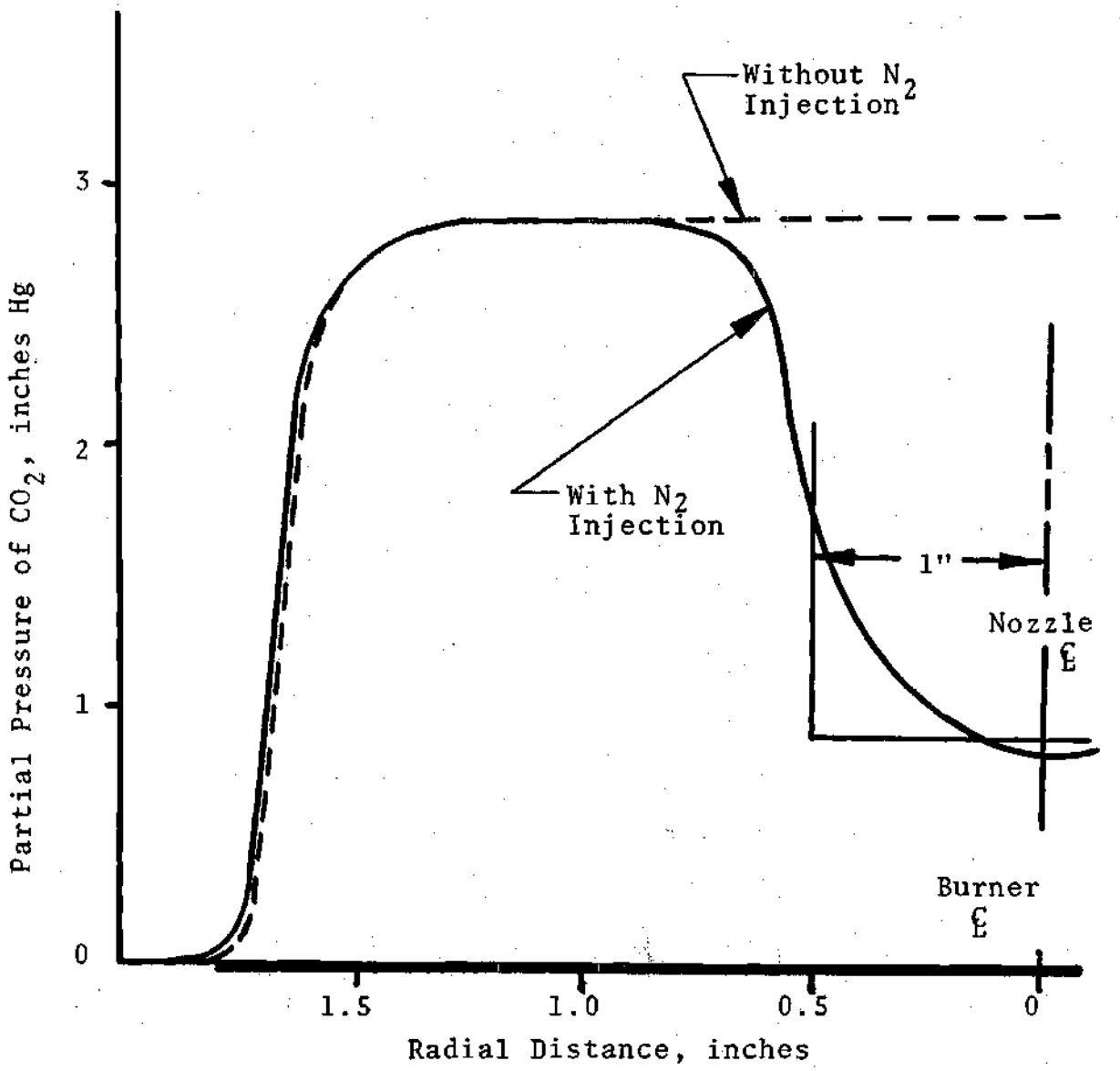

Figure 22. Concentration Profiles of CO_2; Air Flow Rate = 4.142 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.276 lb_m/hr, Φ = 0.898, Sample Taken 1/4 Inch Above Burner

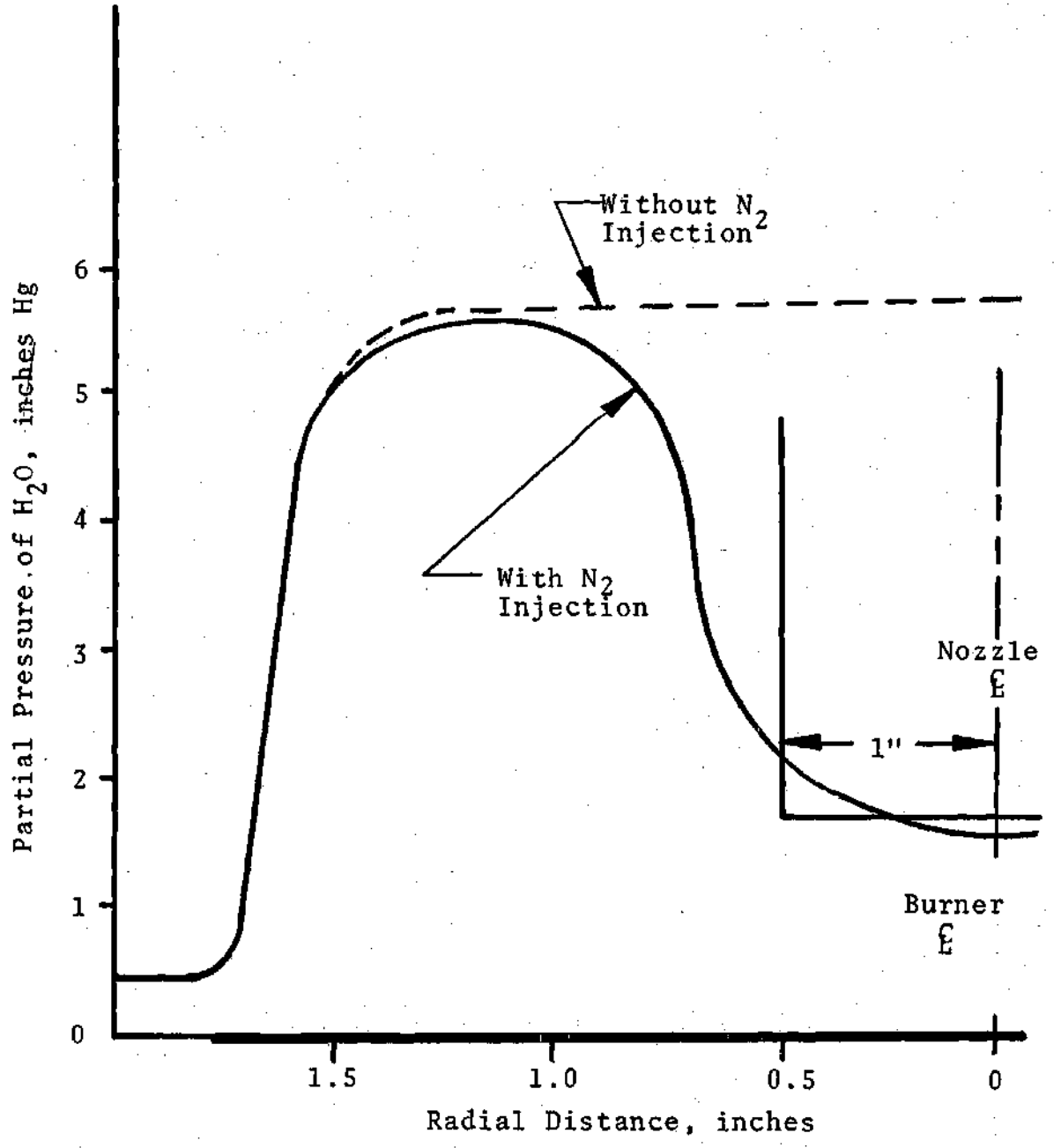

Figure 23. Concentration Profiles of H_2O; Air Flow Rate = 4.142 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.276 lb_m/hr, Φ = 0.898, Sample Taken 1/4 Inch Above Burner

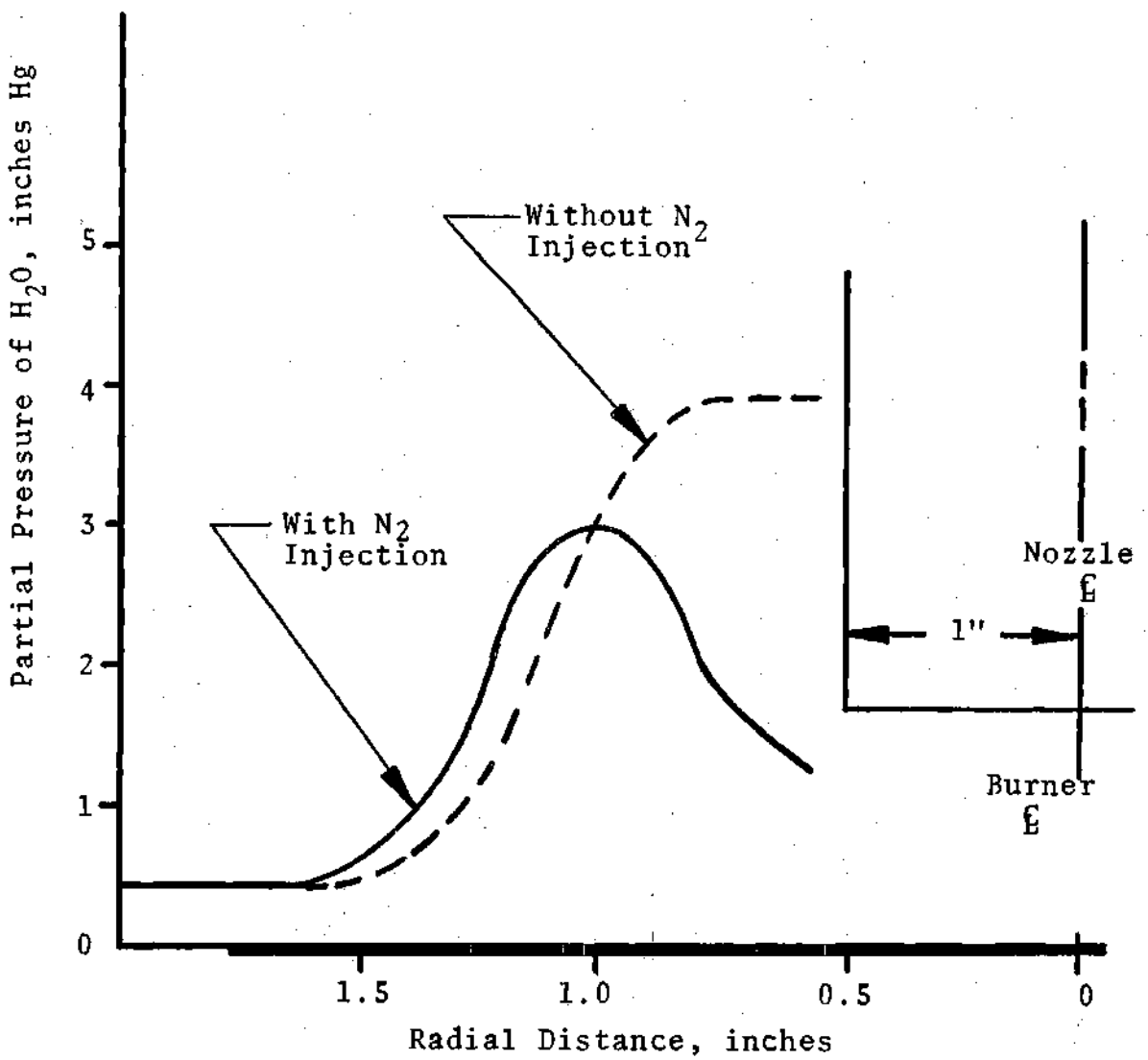

Figure 24. Concentration Profiles of H_2O; Air Flow Rate = 4.855 lb_m/hr, CH_4 Flow Rate = 0.184 lb_m/hr, N_2 Flow Rate = 1.278 lb_m/hr, Φ = 0.648, Sample Taken 1.50 Inches Above Burner

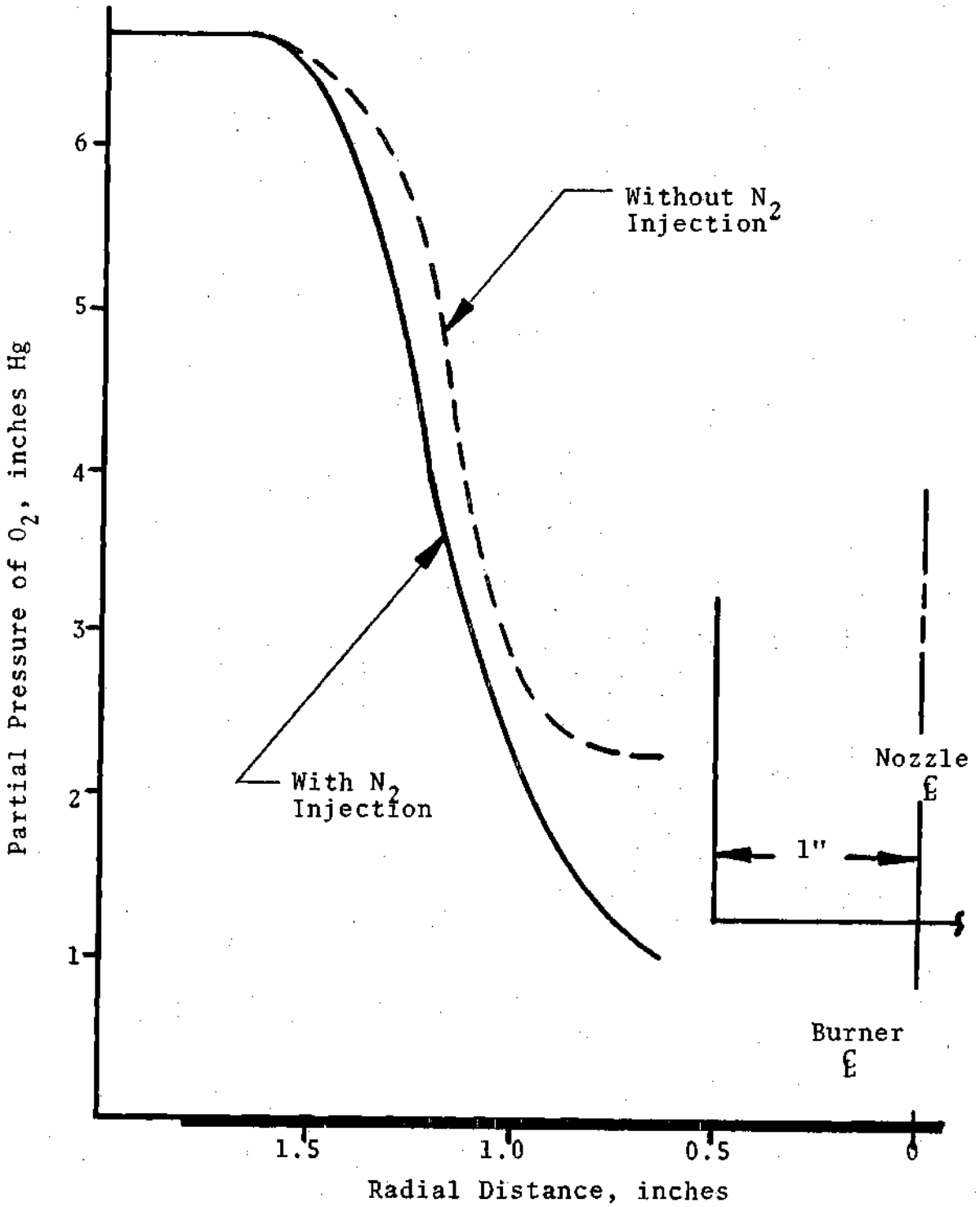

Figure 25. Concentration Profiles of O_2; Air Flow Rate = 4.855 lb_m/hr, CH_4 Flow Rate = 0.184 lb_m/hr, N_2 Flow Rate = 1.278 lb_m/hr, Φ = 0.648, Sample Taken 1.50 Inches Above Burner

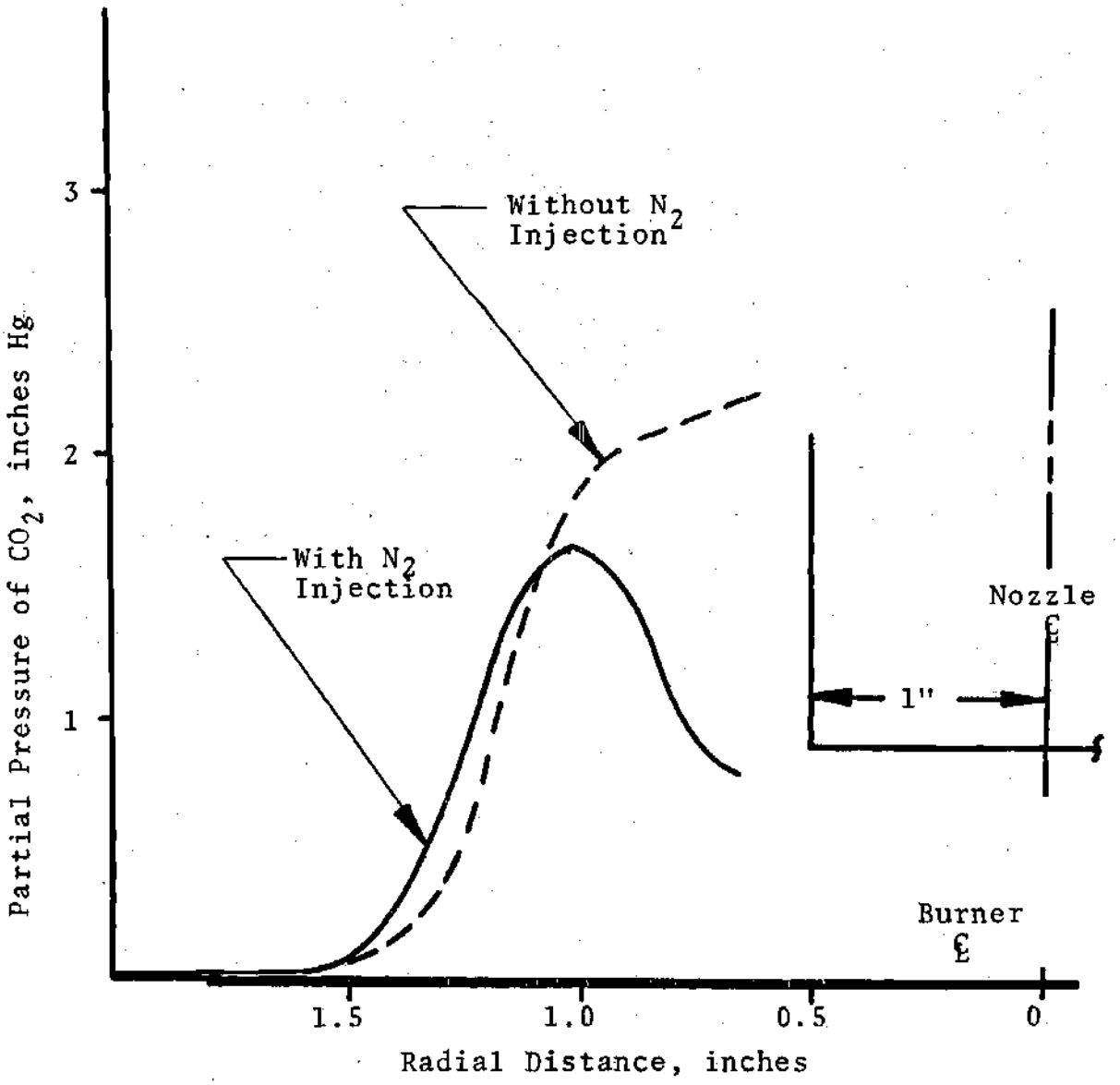

Figure 26. Concentration Profiles of CO_2; Air Flow Rate = 4.855 lb_m/hr, CH_4 Flow Rate = 0.184 lb_m/hr, N_2 Flow Rate = 1.278 lb_m/hr, Φ = 0.648, Sample Taken 1.50 Inches Above Burner

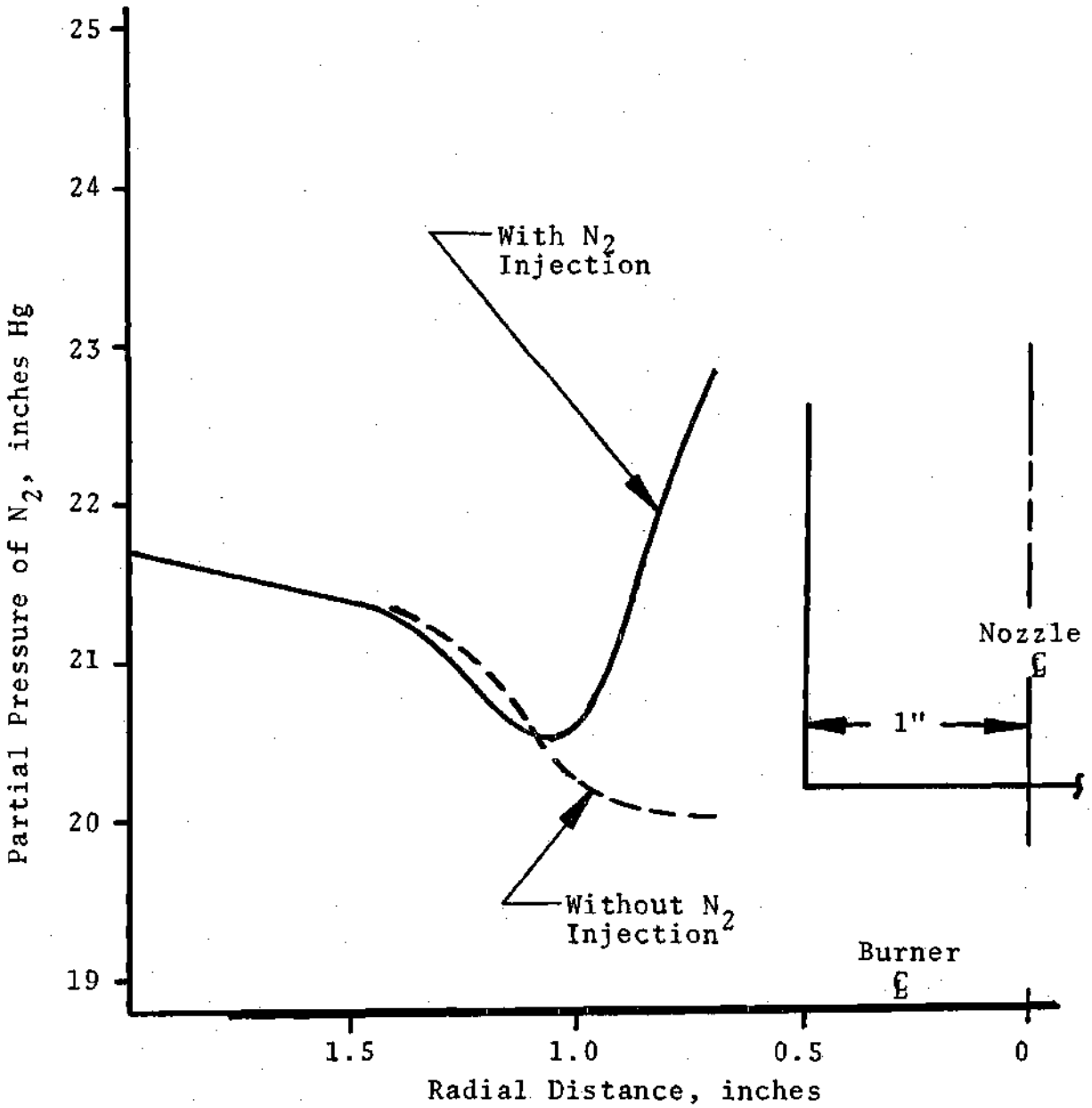

Figure 27. Concentration Profiles of N_2; Air Flow Rate = 4.855 lb_m/hr, CH_4 Flow Rate = 0.184 lb_m/hr, N_2 Flow Rate = 1.278 lb_m/hr, Φ = 0.648, Sample Taken 1.50 Inches Above Burner

sampled is not greatly reduced, creating little disturbance to the flame. The fact that the probe was made of quartz also eliminated any possible catalytic effects on the flame. The shape of the probe also enabled quick quenching of the chemical reaction which also helped to bring good results.

The injection of N_2 into the flame had a great effect on the flame. From the results obtained it is apparent that N_2 injected 0.50 inches from the burner almost destroys or extinguishes the flame. In some cases it caused the flame to lift off the burner matrix prematurely. This, of course, is verified by the fact that the flame species are all greatly reduced and, at the same time, the temperature also decreases dramatically.

Equipment Evaluation

The equipment performed with a high degree of success. In taking temperature measurements the equipment operated essentially the way it was designed to work. There were only two problem areas. First of all, the matrix after constant use would tend to clog up and, as a result, effect the flame. This situation was remedied by changing the matrix every time this problem started to occur. The other problem in measuring the temperature was in making sure the position of the thermocouple was known at all times. This problem was best solved by taking periodic measurements of the thermocouple's position with a metal scale. This was used as a check against the other positioning methods used which did not

guard against movement of the entire tripod assembly.

For the most part, the equipment used in measuring the species concentrations worked in harmony without any major problems. This is of great significance for one of the major goals in this research was to see if this combination of species measuring equipment (gas chromatograph and mass spectrometer) could work effectively and efficiently together using the provided setup. The heating coil that warmed the sampling tubes worked quite well. There seemed to be no blockage or partial blockage due to condensation. One minor problem that existed was in trying to calibrate the gases using the gas chromatograph. It was fairly difficult to obtain the same area under the curve when the same known quantity of a gas was repeatedly injected into the gas chromatograph. It was also equally as difficult to obtain the same area under the curve when the same partial pressure appeared on the mass spectrometer. However, after numerous calibration runs a fairly stable area could be obtained. Other than the great amount of time it took for the equipment to warm up and stabilize the only other problem that occurred was in the sampling of N_2. For some unknown reason the mass spectrometer would constantly drift downward creating a trace as shown in Figure 9. Since the trace drifted at a constant rate a correction factor could be used to straighten the curve out.

After correcting for the above mentioned problems the

total equipment setup worked very well. The results obtained are uniform and fairly accurate. This can now set the stage for further research in this area with refinements in certain areas that lack in accuracy.

CHAPTER V

CONCLUSIONS

As a result of this research it can be concluded that:

1. The equipment designed and the procedures used to move the temperature and gas sampling probes both vertically and horizontally in the flame were successful. All desired positions above the burner matrix were attainable.

2. Condensation of water vapor in the apparatus was prevented while taking species concentration measurements. This, of course, was due to the heating coils wrapped around all of the tubing. If any substantial amount of vapor had condensed it would have given unusual readings on the mass spectrometer, which did not occur.

3. The method used to calibrate the mass spectrometer for each gas species worked. The gas chromatograph worked in complete harmony with the mass spectrometer. This constituted one of the prime objectives of this research.

4. Meaningful temperature and species concentration profiles were obtained from the flame at various heights above the burner matrix. The temperature profiles were always consistent. Also, the total of the partial pressures of all species examined added up quite close to the atmospheric

pressure. This indicates that the method works and also that no major species was left out.

5. The quartz microprobe that was made and used worked quite well. The fact that the probe was heated eliminated, to a great degree, the possibility of the probe acting as a heat sink. Thus, the temperature and the enthalpy in the region being sampled was not greatly reduced, creating little disturbance to the flame. The fact that the probe was made of quartz also eliminated any possible catalytic effects on the flame. The shape of the probe also enalbed quick quenching of the chemical reaction which also helped to bring good results.

6. The injection of N_2 into the flame had a definite effect. In some cases it caused the flame to lift off the burner matrix prematurely. It was also seen that with the injection of N_2 the constituents of the flame directly under the nozzle start to wane along with a temperature decrease.

CHAPTER VI

RECOMMENDATIONS

There are a number of things that could be done in future experimentation that will produce even more accurate results and a greater wealth of knowledge in the field of flat flame research. These recommendations will carry the present work to the next step.

One recommendation is to develop an even more accurate calibration technique for the mass spectrometer to enable the smallest traces of different species to be detected. This may mean the use of numerous columns in the gas chromatograph in order to detect certain species.

Another suggestion is the development of another method to measure the species concentrations in order to check the results obtained in this work. There are several methods discussed in Chapter I that could be used.

As far as the traversing mechanism is concerned, a system should be developed that will enable far more accuracy in the positioning of the probes. Also a better probe gripping device might decrease the amount of probe vibration. If this could be accomplished then it might be possible to investigate the pre-ignition zone of the flame.

In another direction, using the present equipment, it

would be interesting to do more work on the effect of N_2 injection on the flat flame. In doing this it might be advantageous to use just one N_2 flow rate instead of two which were used in this present work. This would give a better picture of just how the N_2 is affecting the flame.

A final recommendation would be to set up a system that would measure the unstable species concentrations in the flat flame. Chapter I discusses other alternatives to probe sampling that could be used to accomplish this task.

The above are just some of the ways in which a continuing effort can be made to acquire more information on the flat flame. This, in turn, will help us to understand more about flame structure in general.

APPENDICES

APPENDIX A

FLOWMETER CALIBRATION CURVES

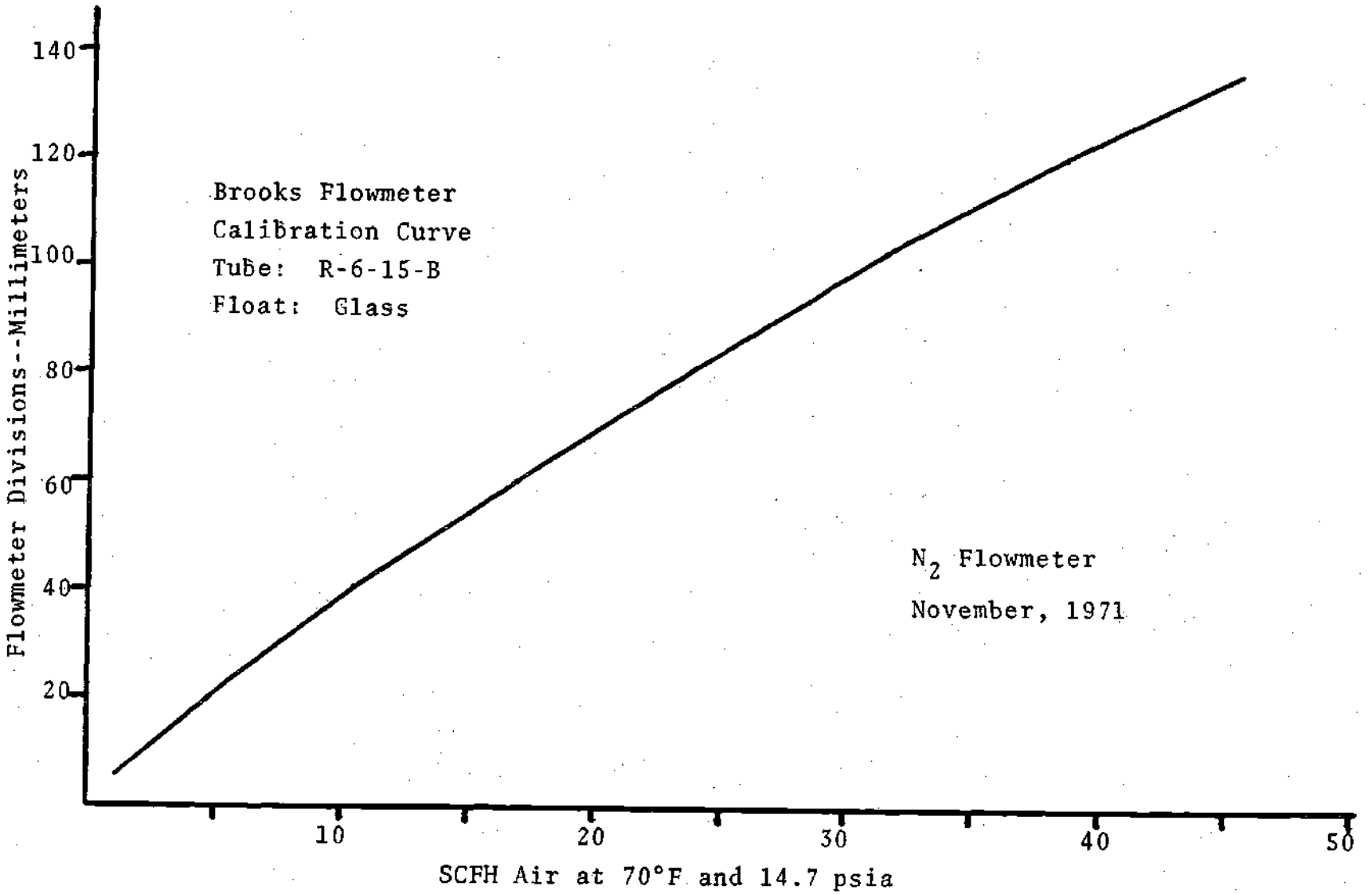

Figure 28. Calibration Curve for the N_2 Flowmeter

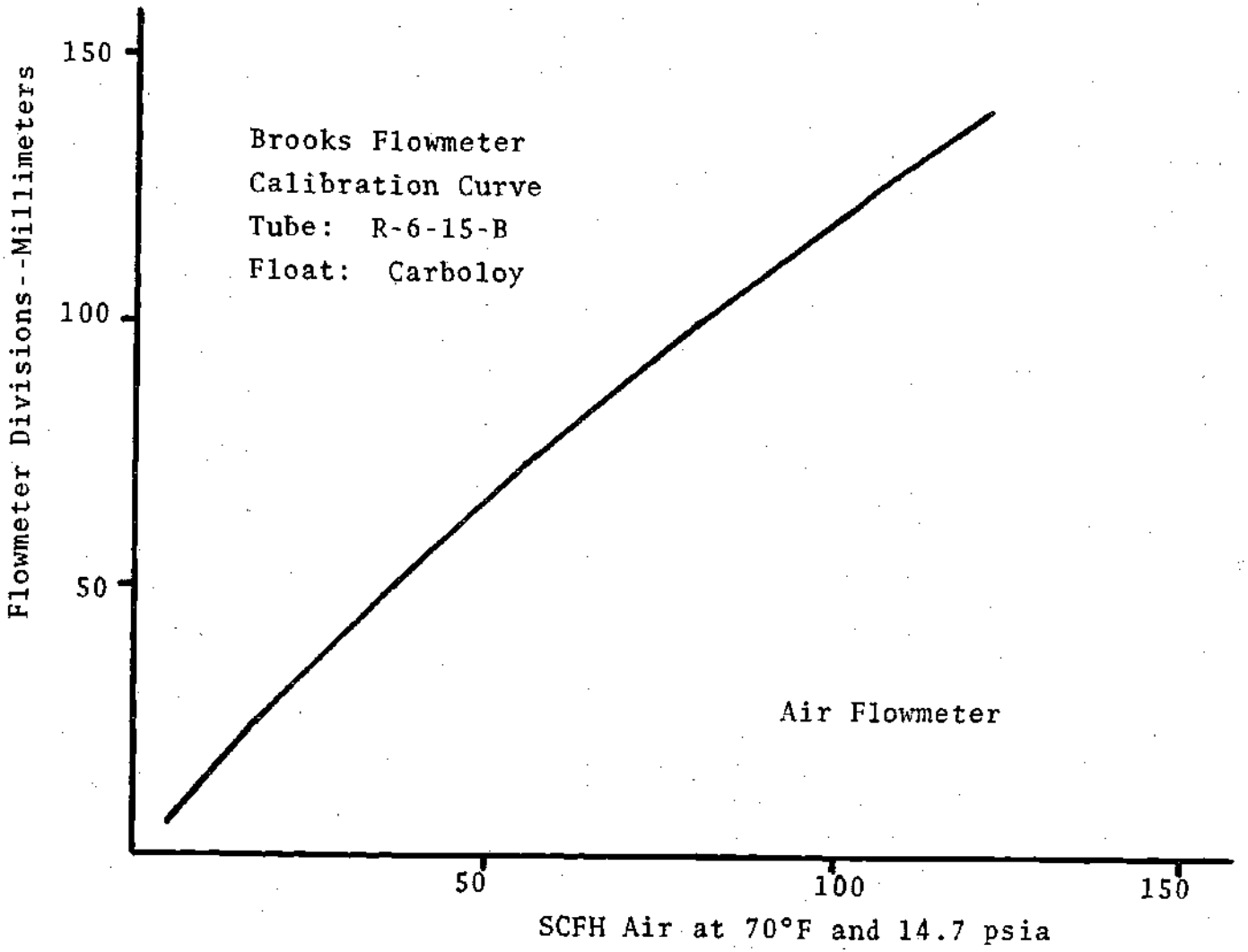

Figure 29. Calibration Curve for the Air Flowmeter

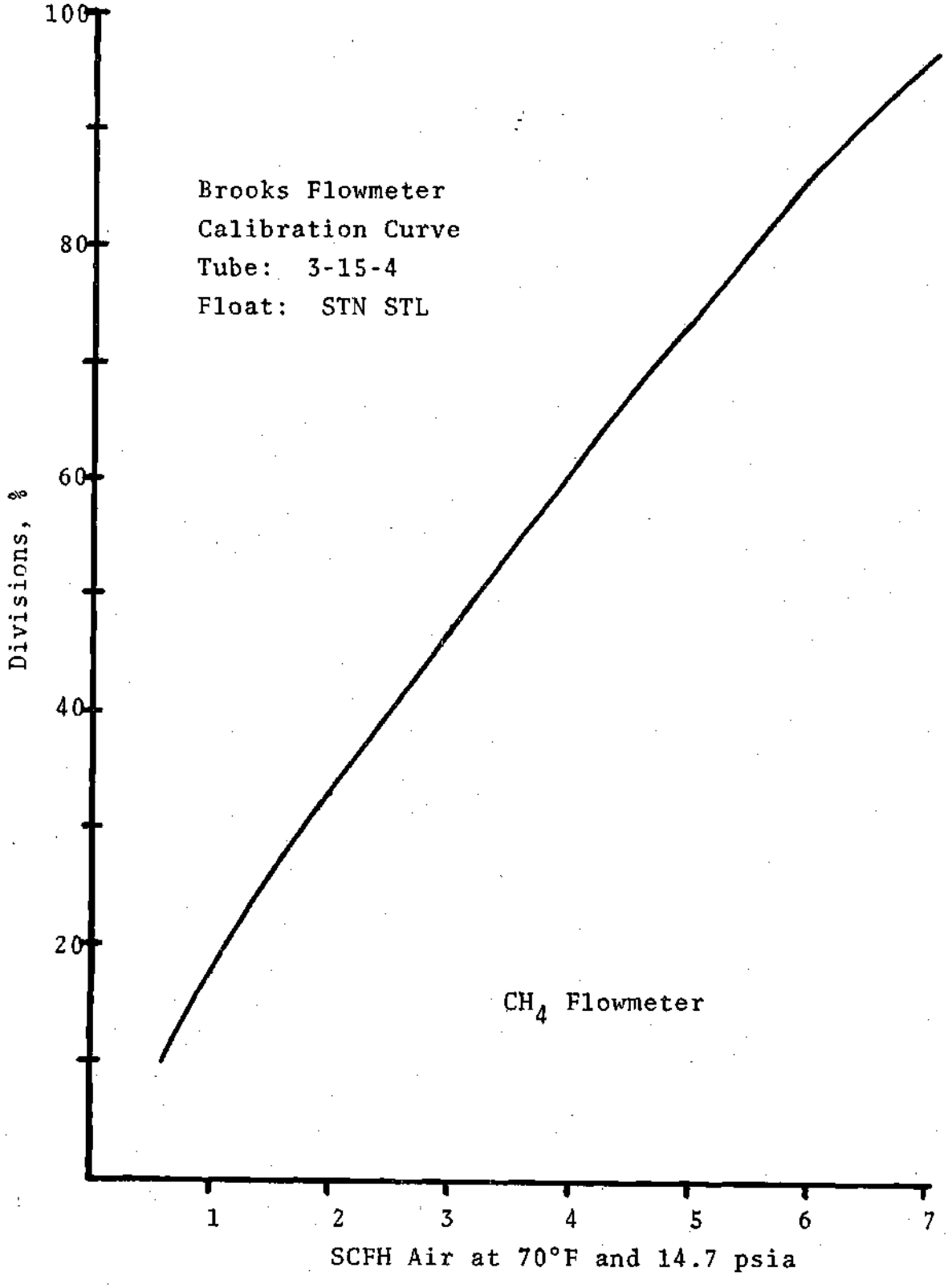

Figure 30. Calibration Curve for the CH_4 Flowmeter

APPENDIX B

SAMPLE CALCULATIONS

The following will demonstrate how the volume and mass flow rates were calculated by the calculator program:

Data given:

1. Barometric pressure--in Hg
2. Air--5 CFH of air at 70°F and 14.7 psia from curve
3. p_a--in Hg gage
4. T_a--°F
5. CH_4--divisions on meter (5 CFH air)
6. p_{CH4}--in oil gage (.834)
7. T_{CH4}--°F
8. N_2--5 CFH air at 70°F and 14.7 psia from curve
9. p_{N2}--in Hg gage
10. T_{N2}--°F

Calculated

1. $\dot{V}_m$--cfh
2. $\dot{m}_a$--lg_m/hr
3. $\dot{m}_a$--g/hr
4. $\dot{V}_{CH4}$--cfh
5. $\dot{m}_{CH4}$--lb_m/hr
6. $\dot{m}_{CH4}$--g/hr

7. A/F ratio
8. ϕ
9. $\dot{V}_{N2}$--cfh
10. $\dot{m}_{N2}$--lb_m/hr
11. $\dot{m}_{N2}$--g/hr

Known

1. 1 atm = 760 mm Hg = 14.696 lb_f/in^2
2. 1 lb_m = 453.69 gm
3. 1 inch = 2.54 cm
4. AF stoichiometric = 17.13 lb_m air/lb_m fuel
5. M_{CH4} = 16.043 lb_m/lb_m mole
6. M_{N2} = 28.016 lb_m/lb_m mole
7. M_{air} = 28.970 lb_m/lb_m mole

a = calibration condition

b = conditions at time of use

$$\dot{V}_b = \dot{V}_a \frac{\gamma_a}{\gamma_b}$$

where $\gamma = \frac{1}{v}$

$$\frac{p}{\gamma} = RT$$

$$\frac{p_a}{\gamma_a} = \frac{1545.31}{28.97} \times 529.688$$

$$\gamma_a = \frac{28.97 \times 14.696 \times 144}{1545.31 \times 529.688}$$

For air:

$$\gamma_b = \frac{28.97 \times p_b \times 144}{1545.31 \times T_b}$$

$$\frac{\gamma_a}{\gamma_b} = \frac{T_b \times 14.7}{P_b \times 529.688}$$

$$\dot{V}_{air} = \dot{V}_a \frac{T_{air} \times 14.696}{P_{air} \times 529.688}$$

and

$$\dot{m}_{air} = \frac{144 \times p_{air} \times \dot{V}_{air} \times 28.97}{1545.31 \times T_{air}}$$

For CH_4:

$$\gamma_b = \frac{16.043 \times P_b \times 144}{1545.31 \times T_b}$$

$$\dot{V}_{CH4} = \dot{V}_a \frac{28.97 \times T_{CH4} \times 14.696}{16.043 \times P_{CH4} \times 529.688}$$

$$\dot{m}_{CH4} = \frac{144 \times P_{CH4} \times \dot{V}_{CH4} \times 16.043}{1545.31 \times T_{CH4}}$$

For N_2:

$$\gamma_b = \frac{28.016 \times P_b \times 144}{1545.31 \times T_b}$$

$$\dot{V}_{N2} = \dot{V}_a \frac{28.97 \times T_{N2} \times 14.696}{28.016 \times P_{N2} \times 529.688}$$

$$\dot{m}_{N2} = \frac{144 \times P_{N2} \times \dot{V}_{N2} \times 28.016}{1545.31 \times T_{N2}}$$

$$\text{Air-Fuel Ratio} = \frac{\dot{m}_{air}}{\dot{m}_{CH4}}$$

$$\Phi = \frac{\text{AF Stoichiometric}}{\text{AF Ratio Actual}}$$

Each method for calculating the gas temperature corrected for radiation which occurs between the thermocouple and the chimney walls is as follows [3]:

Data given:

1. d = thermocouple diameter
2. V = gas velocity
3. E = thermocouple emissivity
4. e = gas emissivity
5. V x d
6. t_m = mean temperature
7. N = from V x d and t_m off of a graph
8. t_c = measured temperature of thermocouple
9. t_w = measured temperature of chimney wall

We will start with the equation:

$$\frac{t_g - t_c}{t_c - t_w} = NdE$$

Next solve for t_g which will be called T_g. Then substitute T_g into the equation

$$x = \frac{T_g^4 - T_w^4}{T_c^4 - T_w^4} e$$

then producing an equation

$$\frac{t_{gr} - t_c}{t_c - t_w} = NdE\ (1-x)$$

Then solve for t_{gr} which is the gas temperature corrected for radiation.

Sample Calculation for Species Concentration

From an average of five trials from the gas chromatograph it was determined that 1 cc or 1 ml of pure N_2 had an area of 92,800 units.

Using the mass spectrometer and gas chromatograph together, when the mass spectrometer registered 650 mm for N_2 an average area of 68,050 units was produced by the gas chromatograph. This meant that .732 ml of N_2 were present. Using the formula

$$P_{\substack{partial \\ N_2}} = \frac{\left(\frac{moles}{liter}\right)_n \left(p_{baro.}\right)}{\left(\frac{moles}{liter}\right)_T}$$

and a barometric pressure = 29.02" Hg

$$P_{\substack{\text{partial} \\ N_2}} = \frac{(.732)(29.02)}{(1)} = 21.24\text{" Hg}$$

This same method was used to calculate the partial pressure of other readings for N_2 as well as for various other species. The points can, of course, be plotted to produce concentration profiles for the various species.

Sample Chemical Equation for Complete Combustion under Adiabatic Conditions

$$CH_4 + a(O_2+3.76\ N_2) + bN_2 \rightarrow x\ CO_2 + y\ H_2O + z\ N_2$$

$$CH_4 + 2(O_2+3.76\ N_2) + N_2 \rightarrow CO_2 + 2H_2O + 8.52\ N_2$$

$$P_{N2} = \frac{8.52}{11.52} \times 14.7 = 10.85 \text{ psia}$$

$$P_{CO2} = \frac{1}{11.52} \times 14.7 = 1.276 \text{ psia}$$

$$P_{H2O} = \frac{1}{11.52} \times 14.7 = 2.55 \text{ psia}$$

$$P_{CH4} = \frac{1}{11.52} \times 14.7 = 1.276 \text{ psia}$$

$$P_{O2} = \frac{1}{11.52} \times 14.7 = 2.55 \text{ psia}$$

$$\text{Air/Fuel} = \frac{2(3.2+3.76(28))}{16} = 17.15 \ \frac{lb_m air}{lb_m fuel}$$

Sample Chemical Equation for Lean Mixture Combustion under Adiabatic Conditions

$$\text{Air/Fuel} = 18.43 \ lb_m air/lb_m fuel$$

$$CH_4 + 2.15\ O_2 + 2.15\ (3.76)\ N_2 \rightarrow v\ CO_2 + y\ H_2O +$$

$$z\ CO + w\ H_2 + q\ O_2 + 2.15\ (3.76)\ N_2$$

$$CO_2 \rightleftharpoons CO + \tfrac{1}{2}\ O_2 \qquad (1)$$

$$CO_2 + H_2 \rightleftharpoons CO + H_2O \qquad (2)$$

$$K_{p1} = \frac{P_{CO}P_{O2}^{1/2}}{P_{CO2}} = \frac{X_{CO}X_{O2}^{1/2}}{X_{CO2}}\ P^{1/2}$$

$$K_{p2} = \frac{P_{CO}P_{H2O}}{P_{CO2}P_{H2}} = \frac{X_{CO}X_{H2O}}{X_{CO2}X_{H2}}\ P^{o}$$

Using an element balance:

For C: $1 = v+z$

O: $4.3 = 2v+y+z+2q$

H: $4 = 2y+2w$

$$n_T = (v+y+z+w+q+8.08)$$

$$K_{p1} = \frac{\frac{z}{n_T}\left(\frac{q}{n_T}\right)^{\frac{1}{2}}}{} p^{\frac{1}{2}} = \frac{zq^{1/2}}{vn_T^{1/2}}$$

$$K_{p2} = \frac{\frac{z}{n_T}\,\frac{y}{n_T}}{\frac{v}{n_T}\,\frac{w}{n_T}} p^{o} = \frac{zy}{vw}$$

$$z = 1-v$$

$$q = 1.65 - \frac{v}{2} - \frac{y}{2}$$

$$y = \frac{2}{1 + \left[\frac{1-v}{vK_{p2}}\right]}$$

$$w = 2-y$$

$$n_T = (12.73 - \frac{y}{2} - \frac{v}{2})$$

$$K_{p1} = \frac{(1-v)(1.65 - \frac{v}{2} - \frac{y}{2})^{1/2}}{v(12.73 - \frac{v}{2} - \frac{y}{2})^{1/2}}$$

$$K_{p1}^{\ 2} = \frac{(1-v)^2(1.65 - \frac{v}{2} - \frac{y}{2})}{v^2(12.73 - \frac{v}{2} - \frac{y}{2})} \qquad (3)$$

After substituting (3) becomes:

$$v^4\left[\frac{K_{p1}^2(K_{p2}-1)}{2} - \frac{(K_{p2}-1)}{2}\right] + v^3[K_{p1}^2K_{p2} - K_{p2} - 12.73\ K_{p1}^2 \quad (4)$$

$$(K_{p2}-1) + \frac{K_{p1}^2}{2} + 2.65\ (K_{p2}-1) - \frac{1}{2}] + v^2[2K_{p2} -$$

$$K_{p1}^2\ 12.73 - 3.80\ (K_{p2}-1) + 2.65] + v[-K_{p2} +$$

$$1.65\ (K_{p2}-1) - 380] + [1.65] = 0$$

Using equation (4)

If $T_2 = 2000°K$
then $K_{p1} = .013$ and $K_{p2} = 4.529$
and $v = .90$

If $T_2 = 3000°K$
then $K_{p1} = .327$ and $K_{p2} = 7.211$
and $v = .41$

If $T_2 = 4500°K$
then $K_{p1} = 11.99$ and $K_{p2} = 8.831$
and $v = .055$

Next, the equation

$$\Delta H = \Delta H_1 + \Delta H^o_{To} + \Delta H_2 = 0 \quad (5)$$

is used

$$H_1 = 0$$

$$H_2 = \sum_p n_p \, (h_{T2}-h_{T0})_p$$

$$H^o_{T0} = \sum_p n_p \, h^o_{fp} - \sum_r n_r \, h^o_{fr}$$

Substituting into equation (5)

$$H = v h_{f_{CO2}} + \left\{\frac{2}{1 + \frac{1-v}{vK_{p2}}}\right\} h^o_{f_{H2O}} + (1-v)h^o_{f_{CO}} - \qquad (6)$$

$$h^o_{f_{CH4}} + v(h_{T2}-h_{T0})_{CO2} + \left\{\frac{2}{1 + \frac{1-v}{vK_{p2}}}\right\} (h_{T2}-h_{T0})_{H2O}$$

$$+ (1-v)(h_{T2}-h_{T0})_{CO} + \left\{2 - \frac{2}{1 + \frac{1-v}{vK_{p2}}}\right\} (h_{T2}-h_{T0})_{H2}$$

$$+ \left\{1.65 - \frac{v}{2} - \frac{1}{1 + \frac{1-v}{vK_{p2}}}\right\} (h_{T2}-h_{T0})_{O2}$$

$$+ (2.15)(3.76)(h_{T2}-h_{T0})_{N2} = 0$$

At 2000°K

$$K_{p2} = 4.529$$

and $v = .742$

At 3000°K $K_{p2} = 7.211$

and $v = 2.19$

At 1500°K $K_{p2} = 2.56$

and $v = .44$

Thus, by plotting temperature vs. v for equations (4) and (6) the adiabatic flame temperature for an A/F ratio of 18.43 is 2100°K which makes $v = .85$

$z = .15$

$y = 1.66$

$w = 0.34$

$q = 0.40$

$K_{p2} = 4.875$

Thus, we get the balanced equation:

$$CH_4 + 2.15\ O_2 + 2.15\ (3.76)\ N_2 \rightarrow .85\ CO_2 + 1.66\ H_2O \quad (7)$$

$$+ .15\ CO + .34\ H_2 + .40\ O_2 + 2.15\ (3.76)\ N_2$$

The partial pressures before combustion are:

$$P_{O2} = 2.81 \text{ psia}$$

$$P_{N2} = 10.58 \text{ psia}$$

$$P_{CH4} = 1.31 \text{ psia}$$

The partial pressures after combustion are:

$$P_{CO2} = 1.09 \text{ psia}$$

$$P_{H2O} = 2.13 \text{ psia}$$

$$P_{CO} = 0.19 \text{ psia}$$

$$P_{H2} = 0.44 \text{ psia}$$

$$P_{O2} = 0.51 \text{ psia}$$

$$P_{N2} = 10.35 \text{ psia}$$

APPENDIX C

TEMPERATURE PROFILES

The following figures demonstrate the equipment in operation while at various sampling distances above the matrix. A summary of what is included may be seen in Table 2 of Chapter IV.

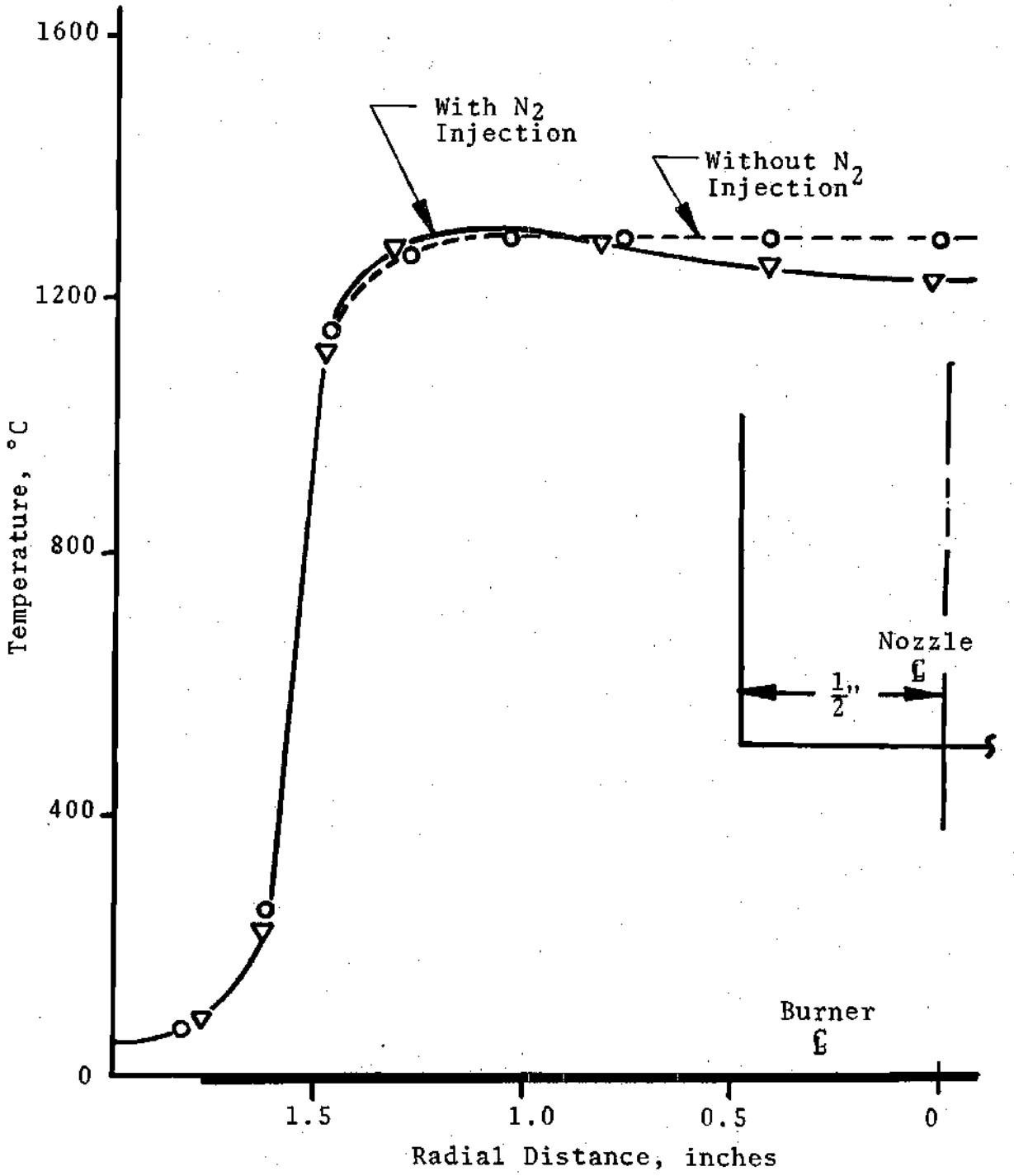

Figure 31. Flame Temperature Profiles; Air Flow Rate = 2.89 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.645, Sample Taken 0.125 Inches Above Burner

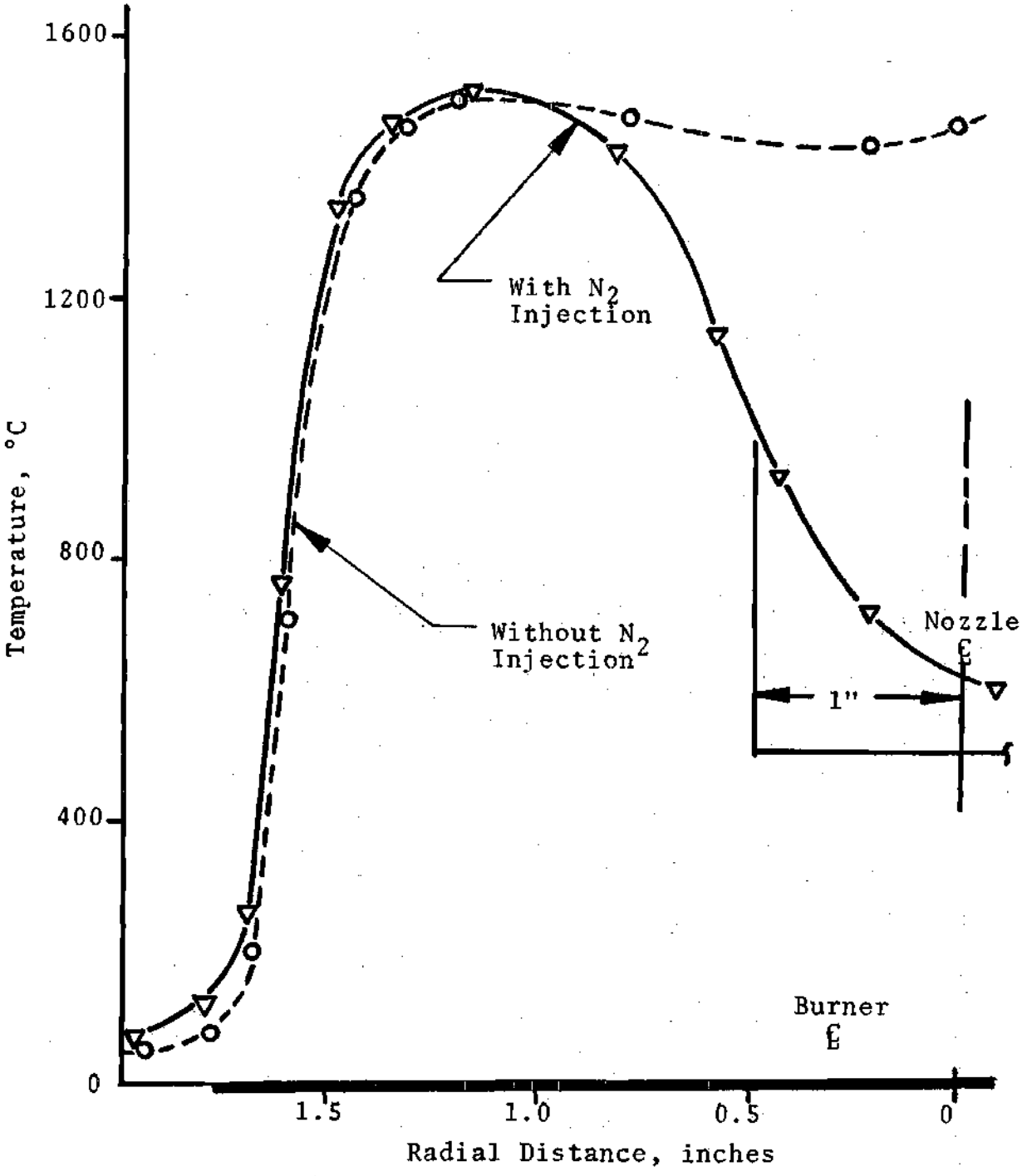

Figure 32. Flame Temperature Profiles; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.898, Sample Taken 0.25 Inch Above Burner

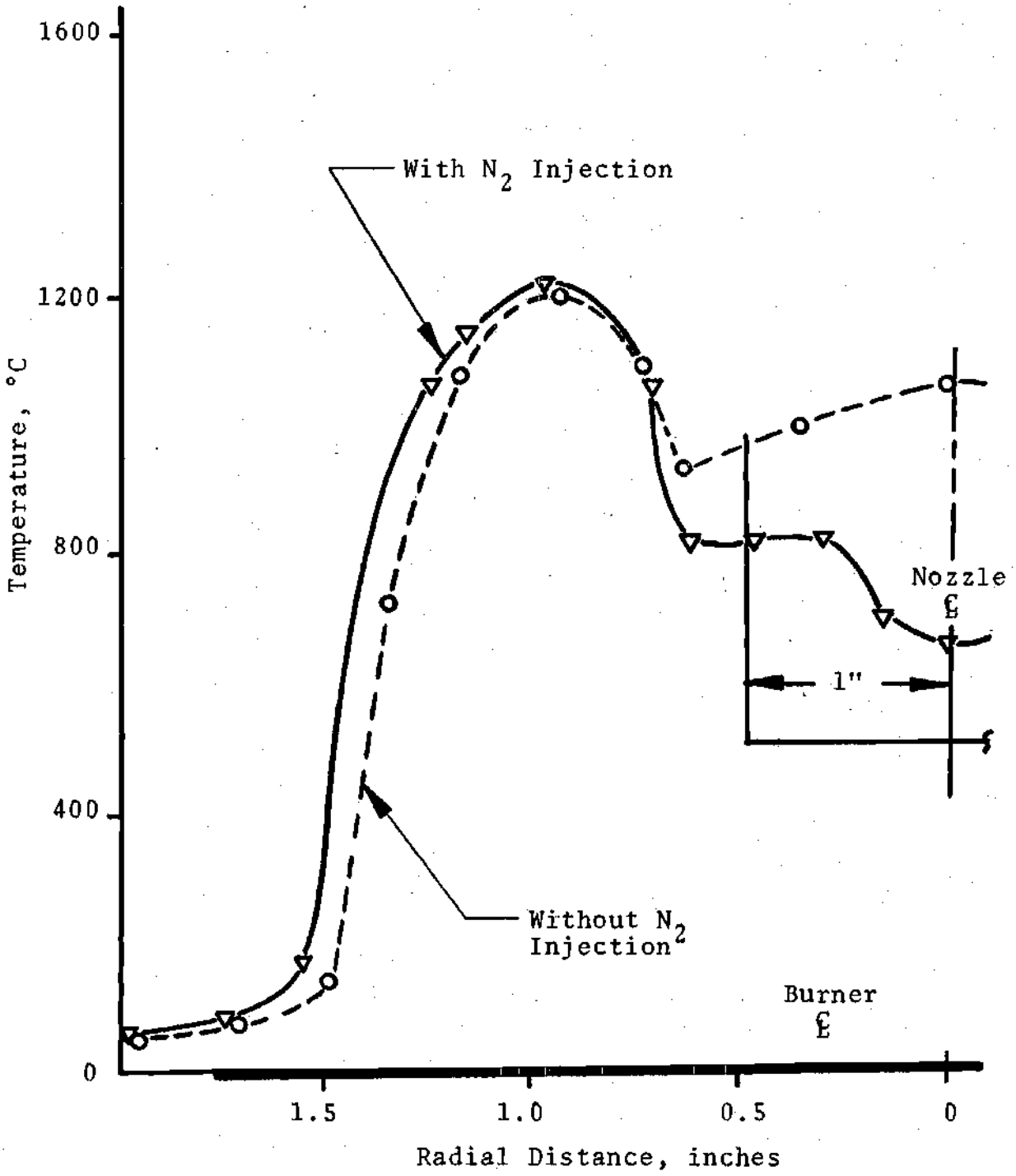

Figure 33. Flame Temperature Profiles; Air Flow Rate = 2.23 lb_m/hr, CH_4 Flow Rate = 0.118 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.906, Sample Taken 0.5 Inches Above Burner

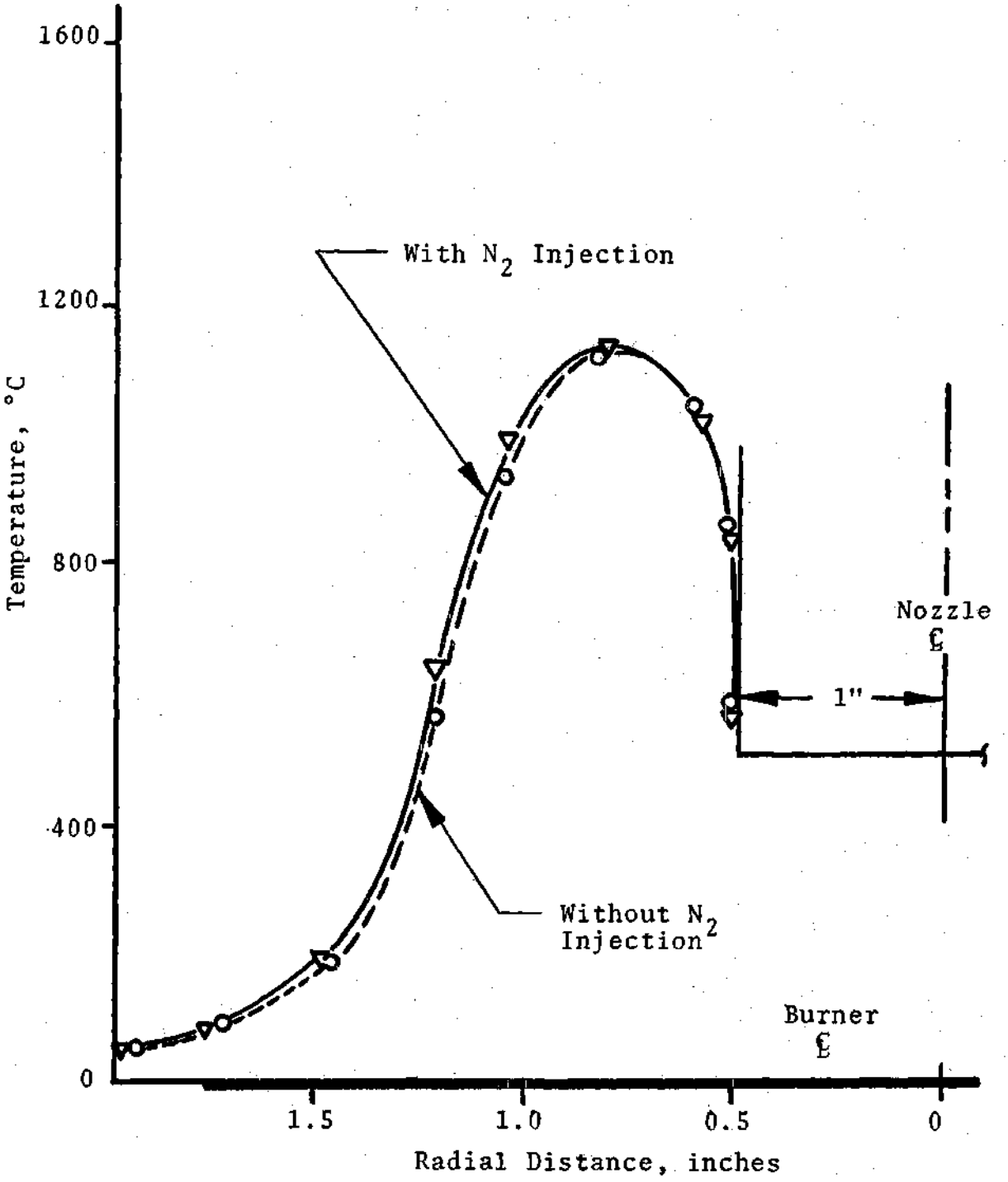

Figure 34. Flame Temperature Profiles; Air Flow Rate = 2.86 lb_m/hr, CH_4 Flow Rate = 0.108 lb_m/hr, N_2 Flow Rate = 0.200 lb_m/hr, Φ = 0.645, Sample Taken 0.75 Inches Above Burner

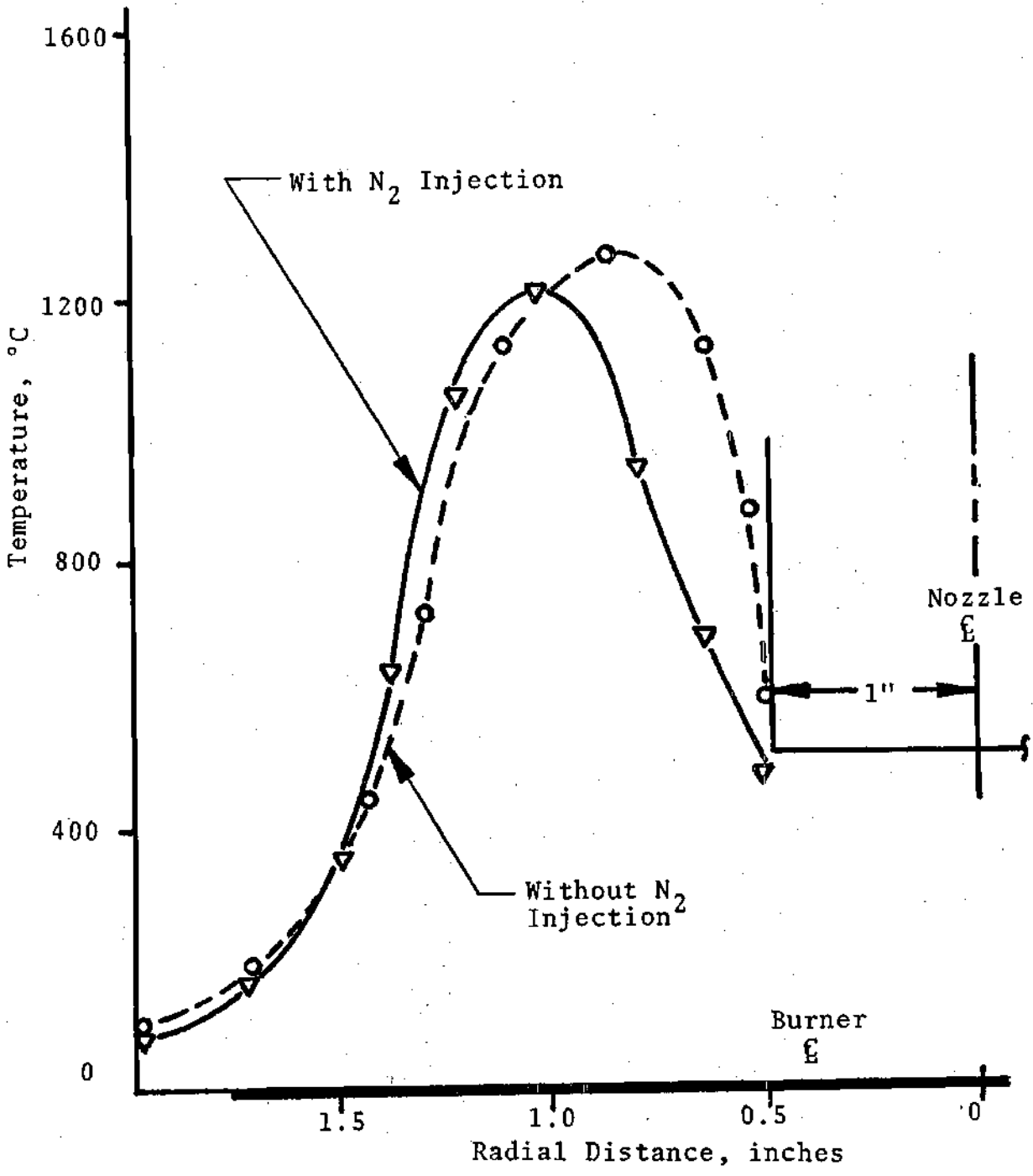

Figure 35. Flame Temperature Profiles; Air Flow Rate = 4.81 lb_m/hr, CH_4 Flow Rate = 0.182 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.647, Sample Taken 1.0 Inch Above Burner

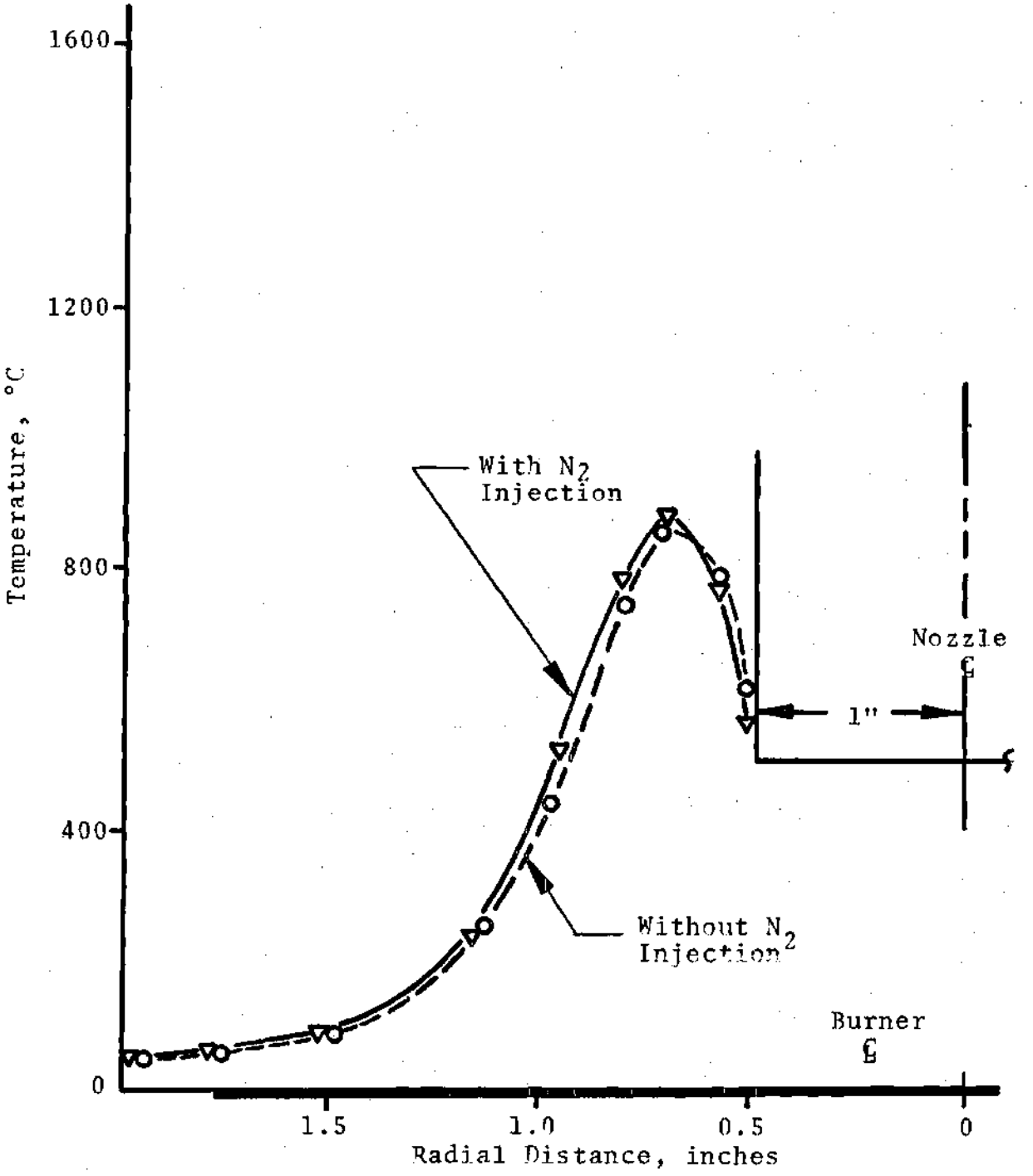

Figure 36. Flame Temperature Profiles; Air Flow Rate = 2.87 lb_m/hr, CH_4 Flow Rate = 0.108 lb_m/hr, N_2 Flow Rate = 0.201 lb_m/hr, Φ = 0.644, Sample Taken 1.5 Inches Above Burner

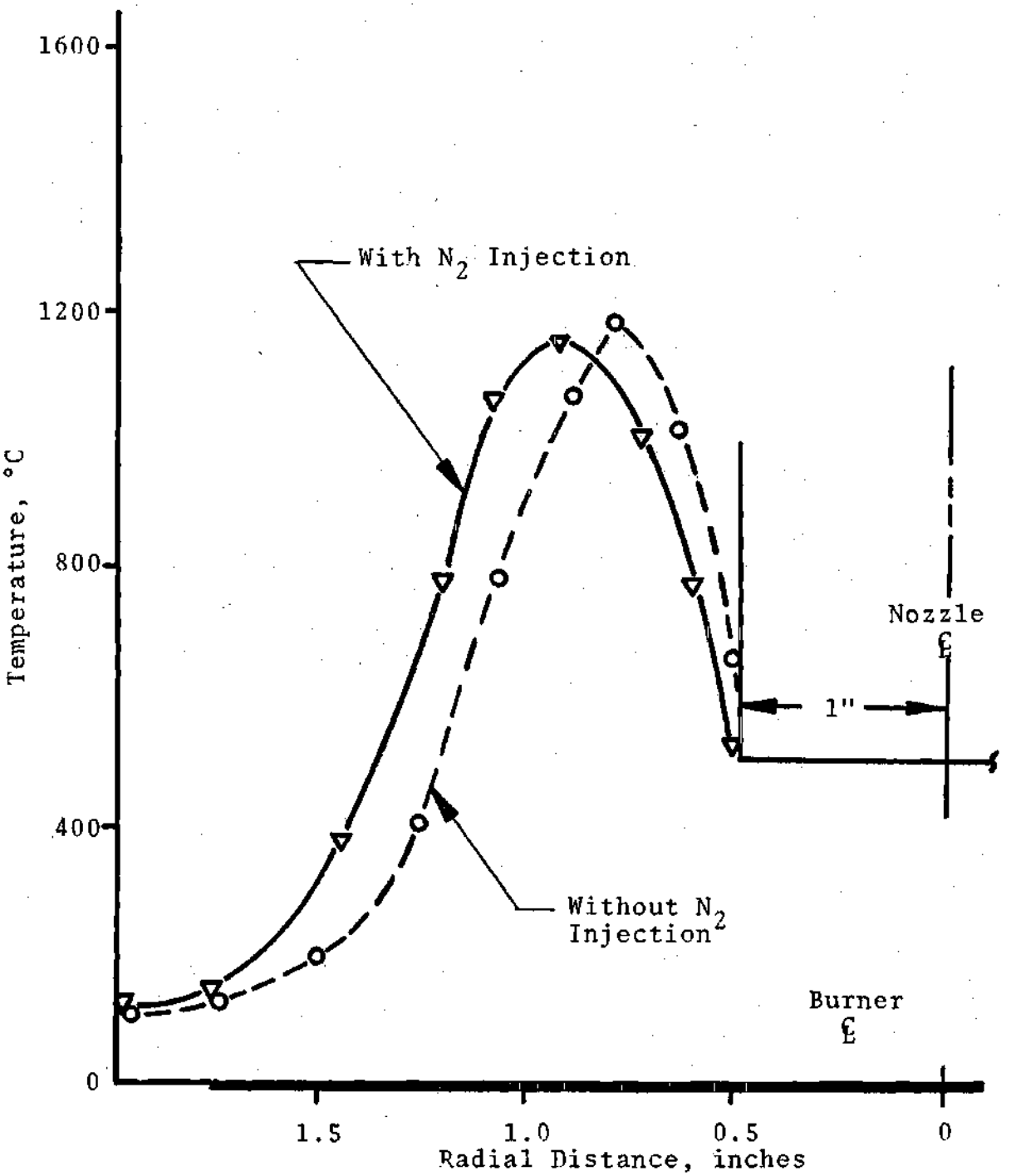

Figure 37. Flame Temperature Profiles; Air Flow Rate = 4.096 lb_m/hr, CH_4 Flow Rate = 0.215 lb_m/hr, N_2 Flow Rate = 1.27 lb_m/hr, Φ = 0.897, Sample Taken 1.50 Inches Above Burner

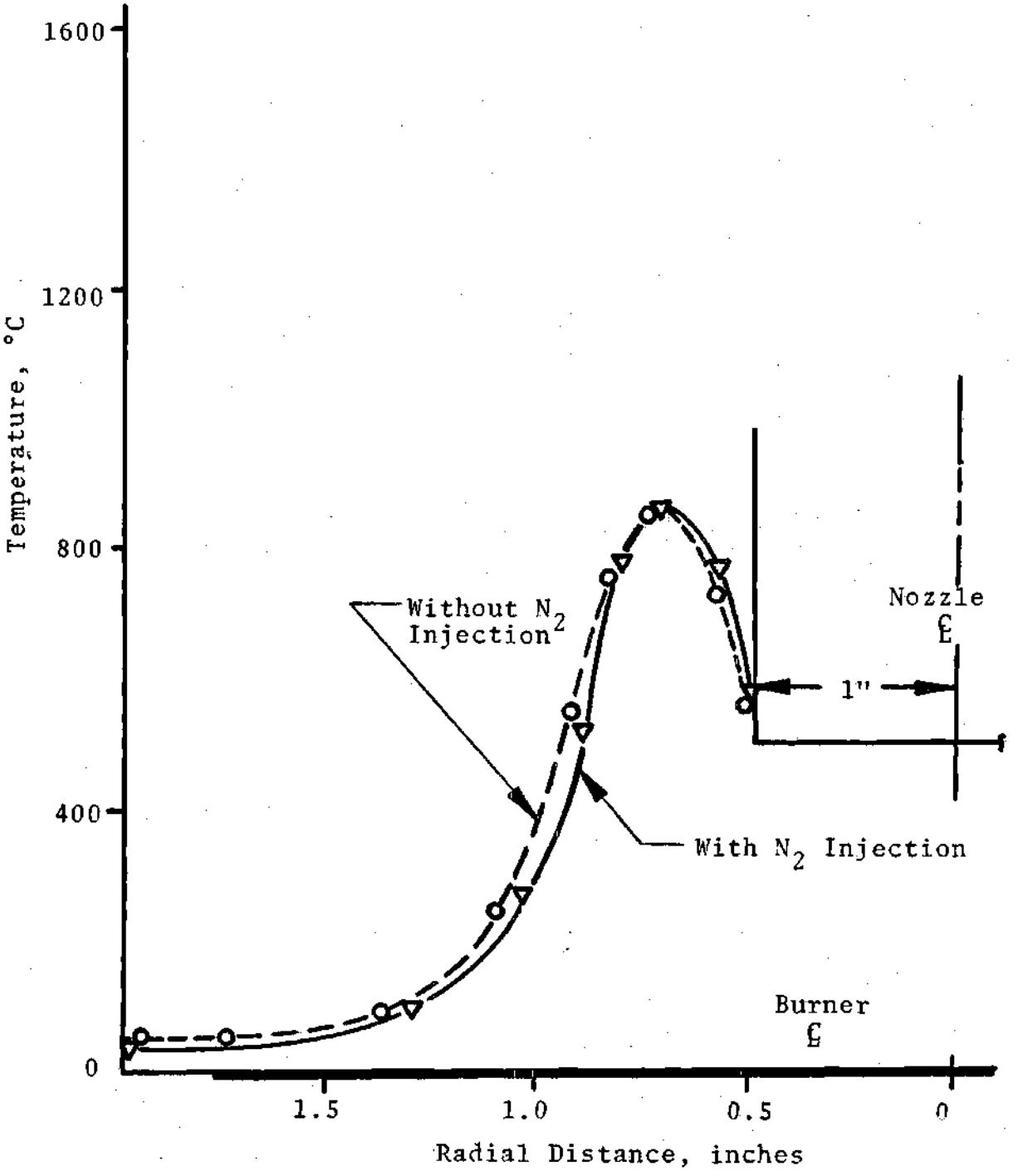

Figure 38. Flame Temperature Profiles; Air Flow Rate = 2.89 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.645, Sample Taken 2.0 Inches Above Burner

APPENDIX D

CONCENTRATION PROFILES

The following figures demonstrate the equipment in operation while at various sampling distances above the matrix. A summary of what is included may be seen in Table 4 of Chapter IV.

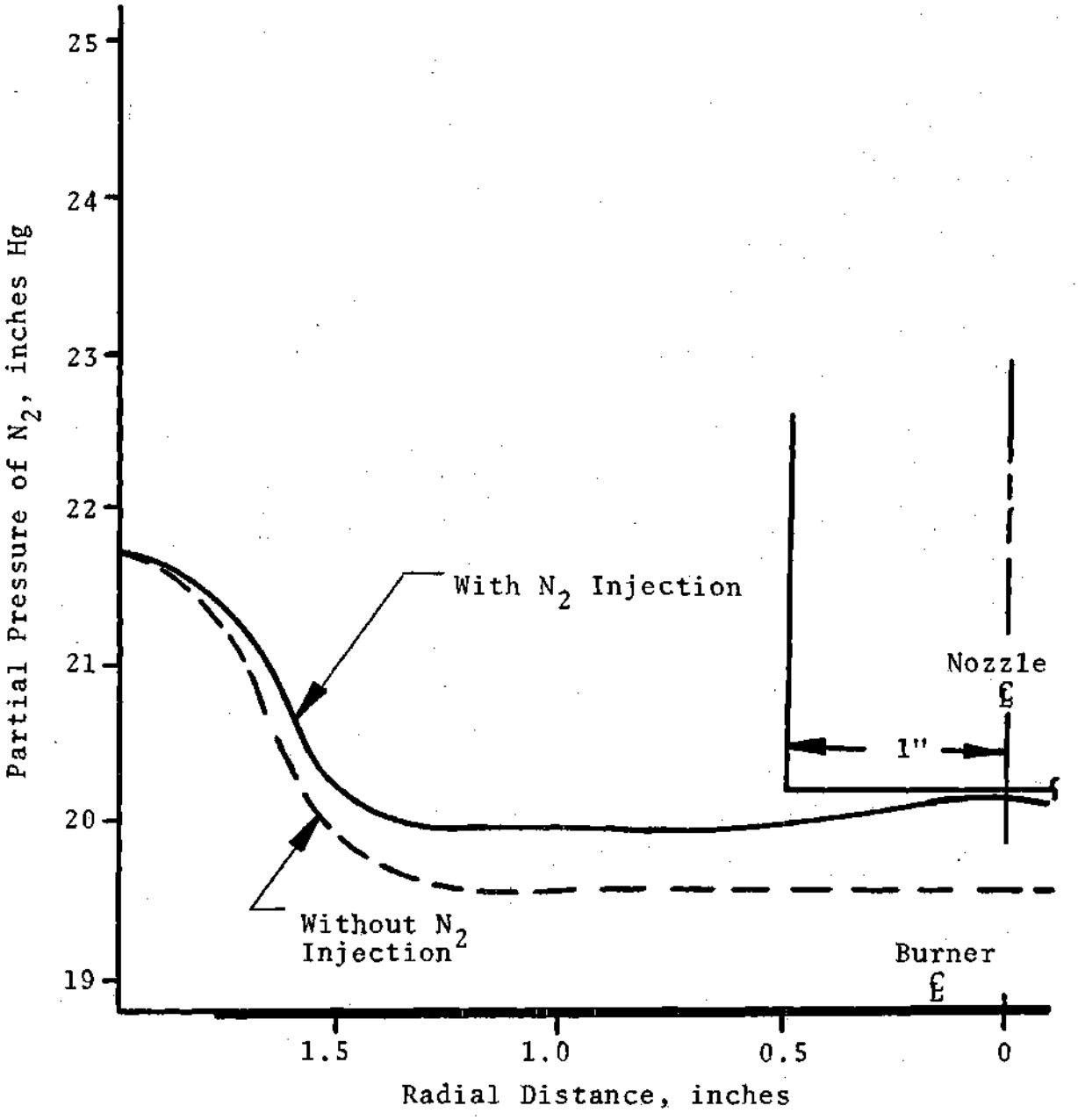

Figure 39. Concentration Profiles of N_2; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 0.125 Inch Above Burner

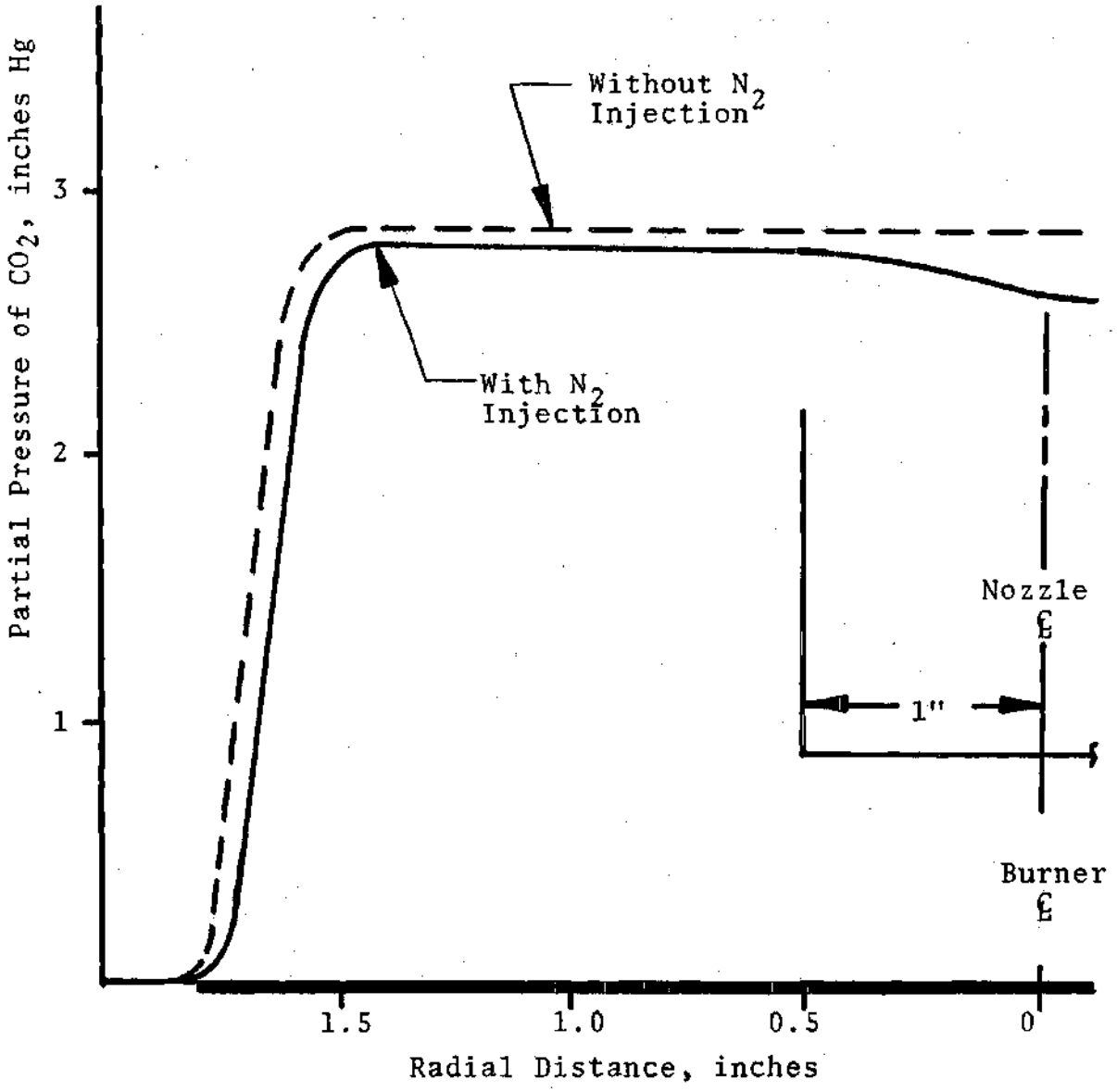

Figure 40. Concentration Profiles of CO_2; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 0.125 Inch Above Burner

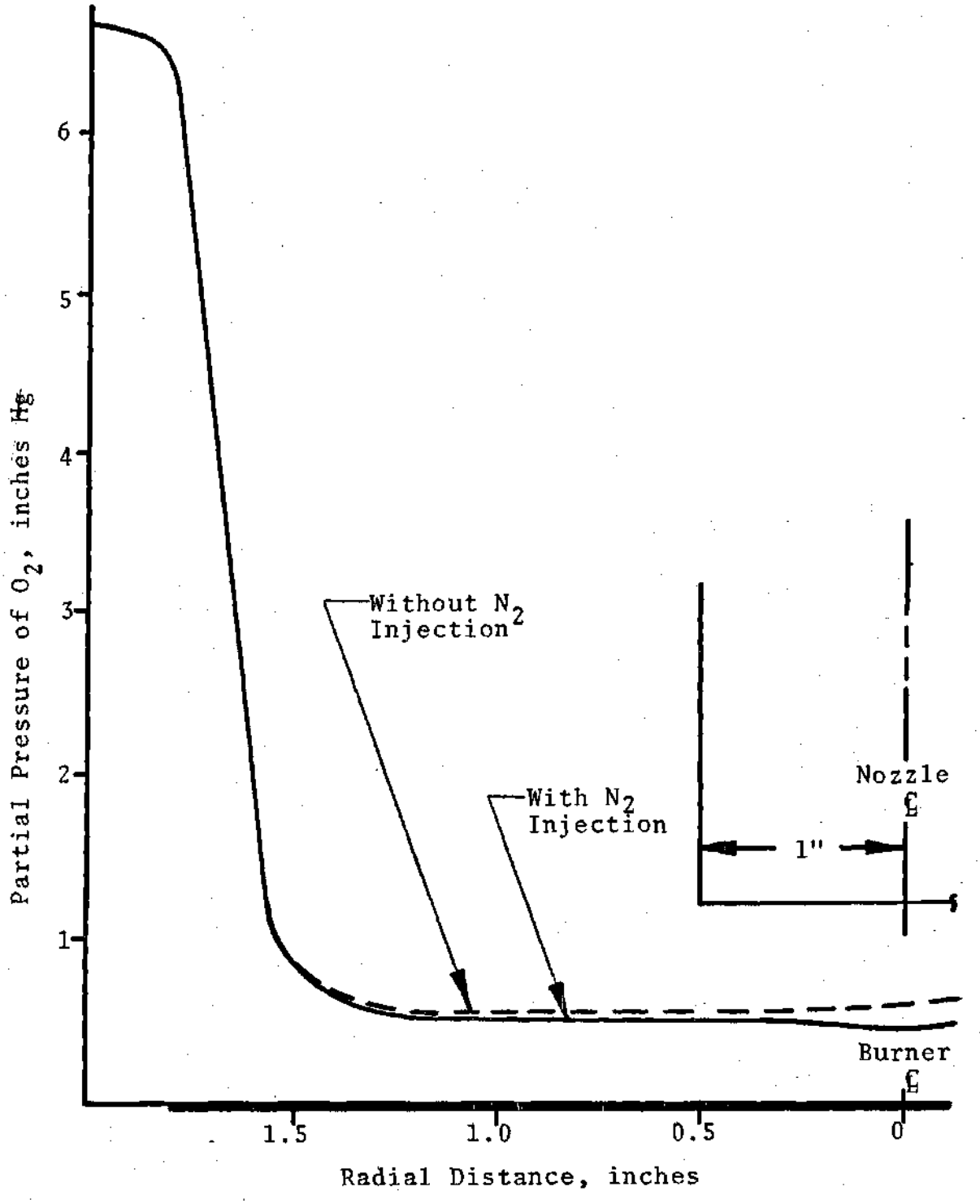

Figure 41. Concentration Profiles of O_2; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 0.125 Inch Above Burner

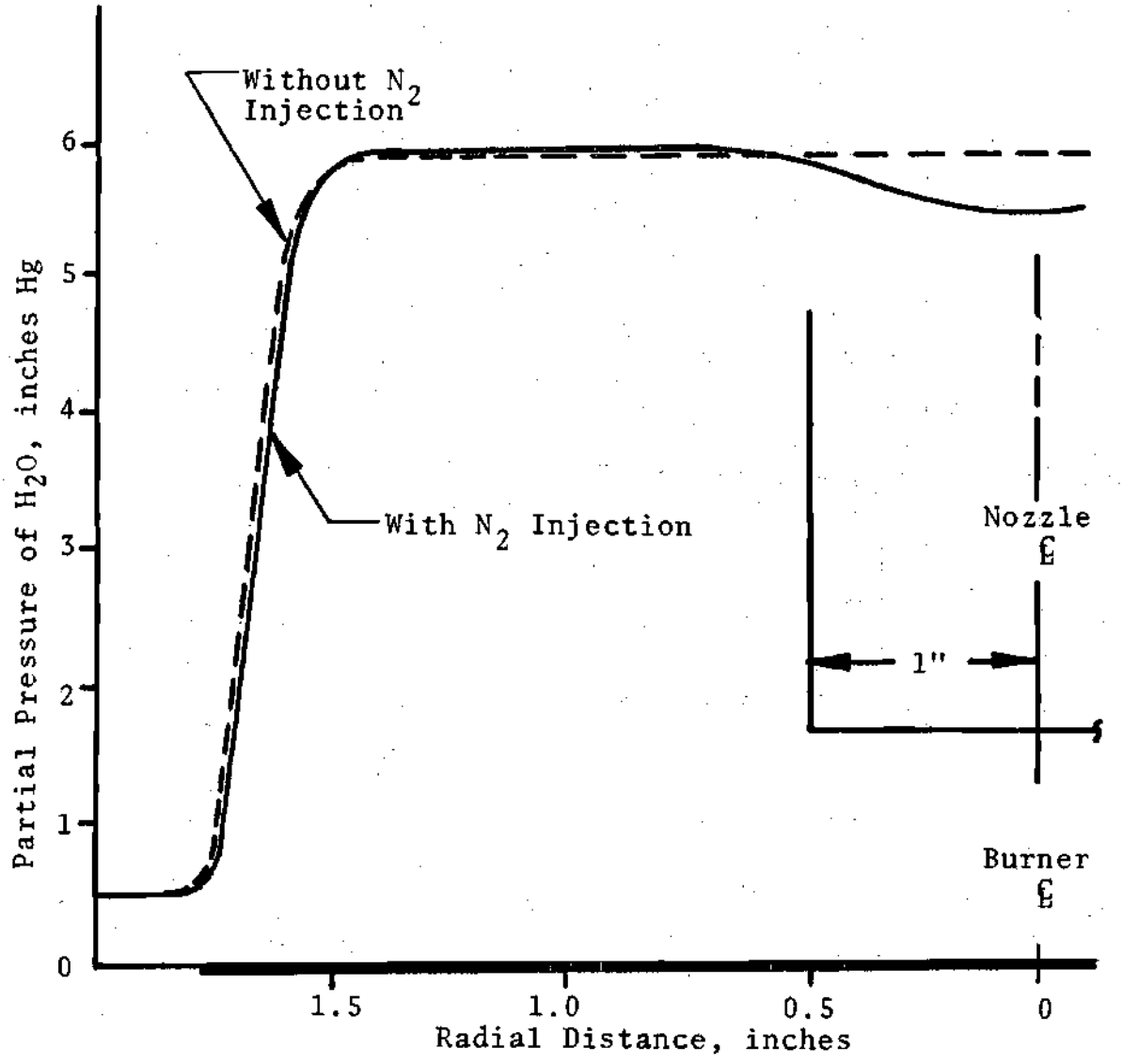

Figure 42. Concentration Profiles of H_2O: Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.217 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 0.125 Inch Above Burner

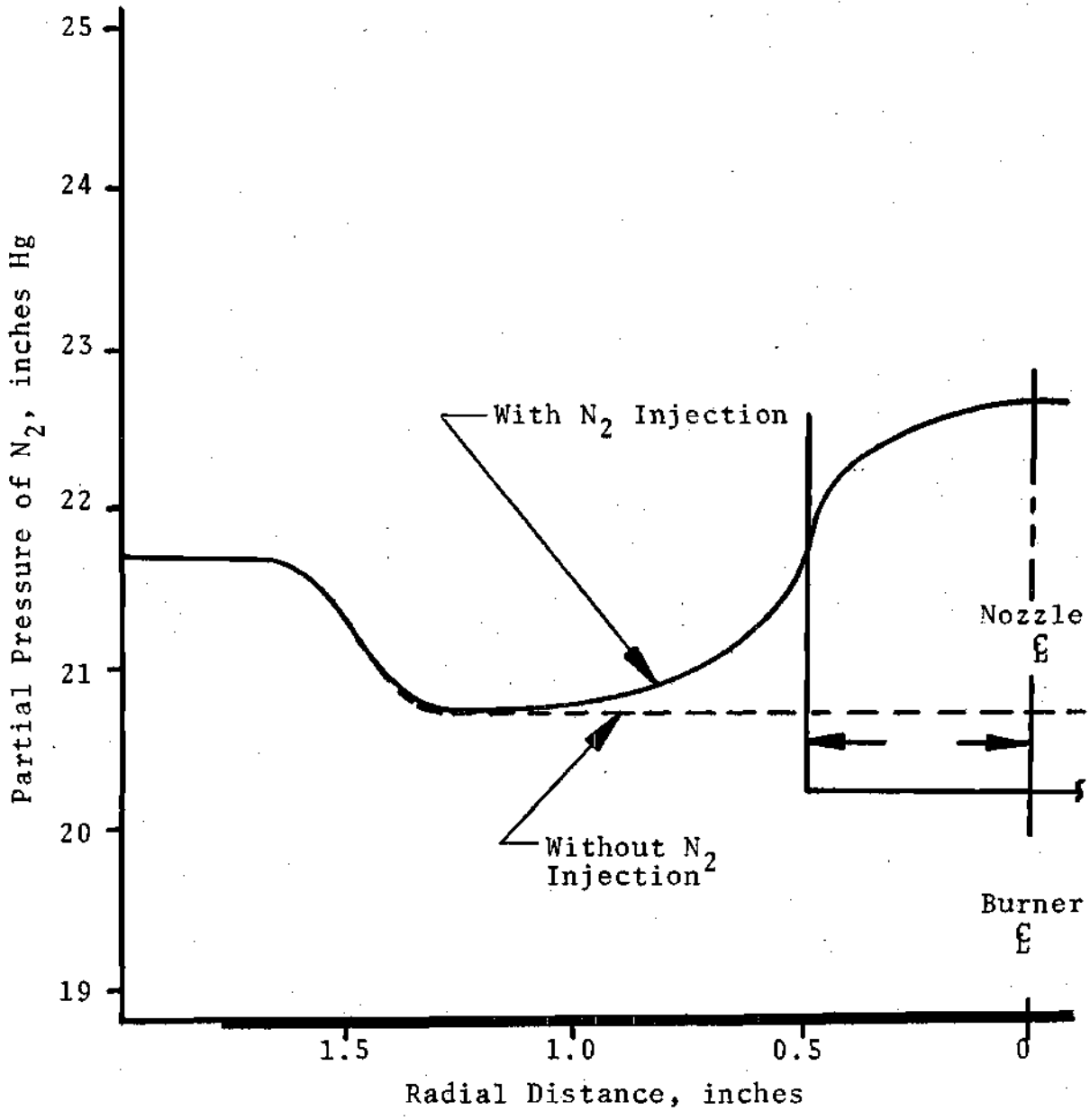

Figure 43. Concentration Profiles of N_2; Air Flow Rate = 2.88 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.646, Sample Taken 0.50 Inch Above Burner

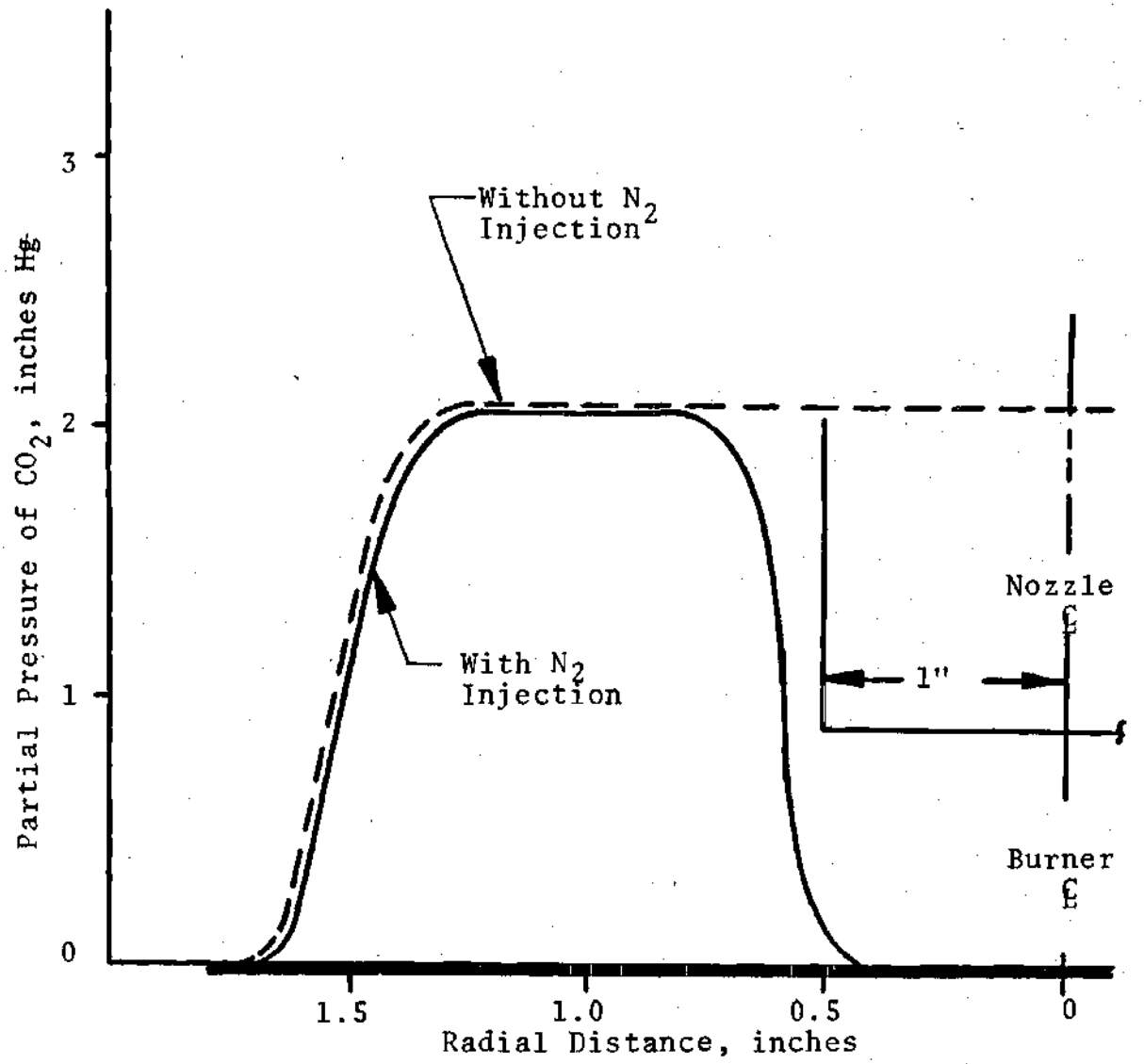

Figure 44. Concentration Profiles of CO_2; Air Flow Rate = 2.88 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.646, Sample Taken 0.50 Inch Above Burner

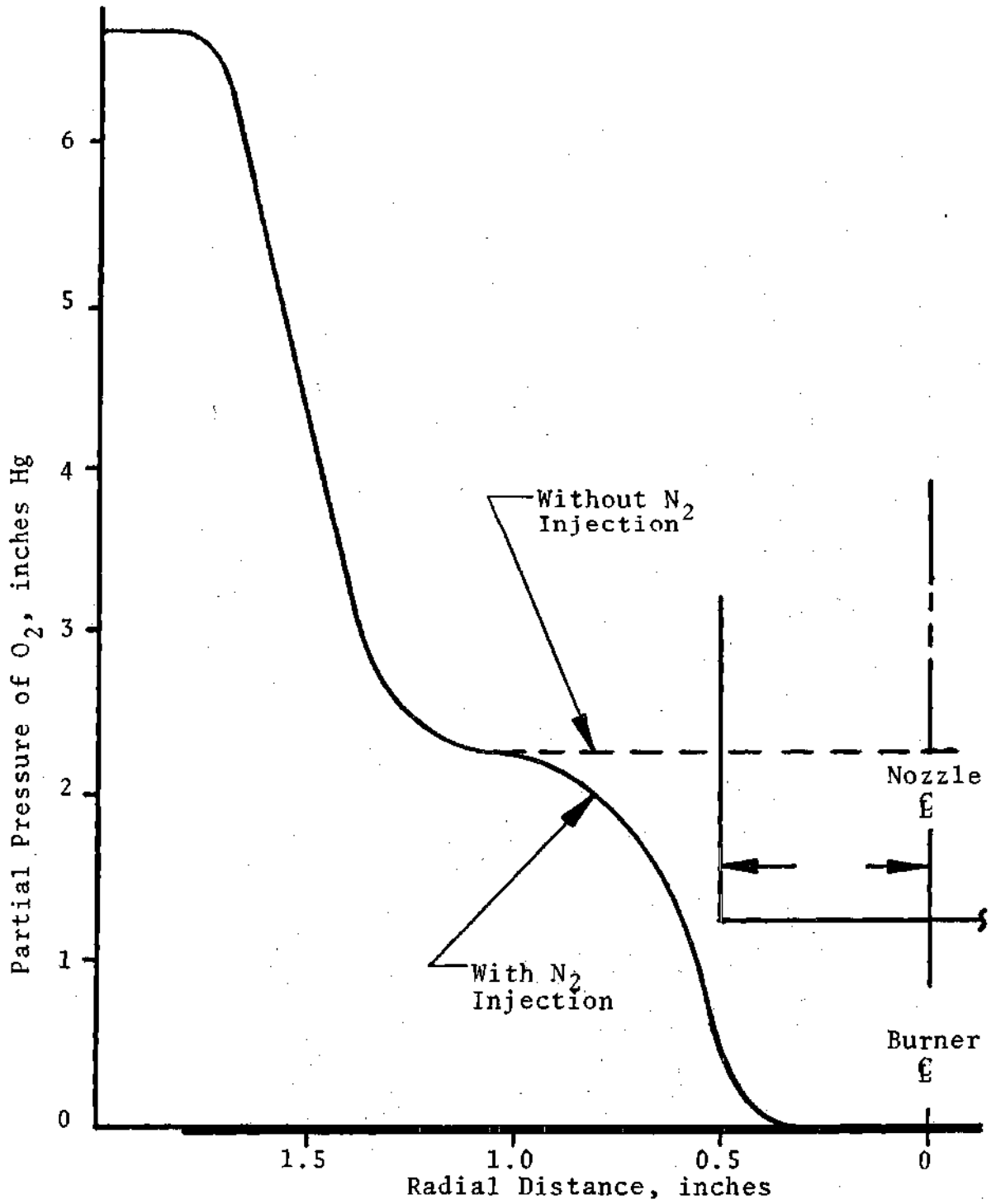

Figure 45. Concentration Profiles of O_2; Air Flow Rate = 2.88 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.646, Sample Taken 0.50 Inch Above Burner

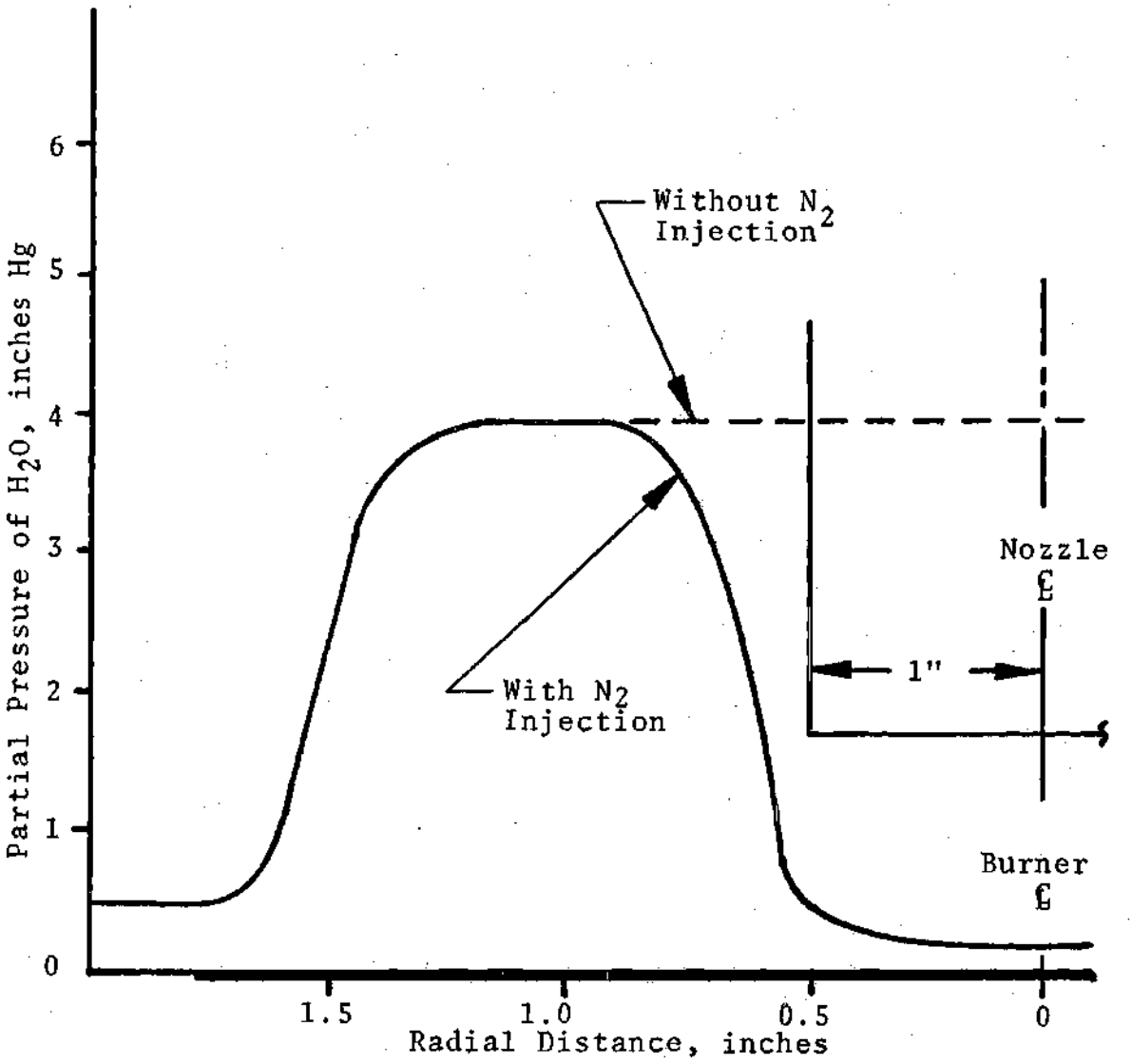

Figure 46. Concentration Profiles of H_2O; Air Flow Rate = 2.88 lb_m/hr, CH_4 Flow Rate = 0.109 lb_m/hr, N_2 Flow Rate = 0.202 lb_m/hr, Φ = 0.646, Sample Taken 0.50 Inch Above Burner

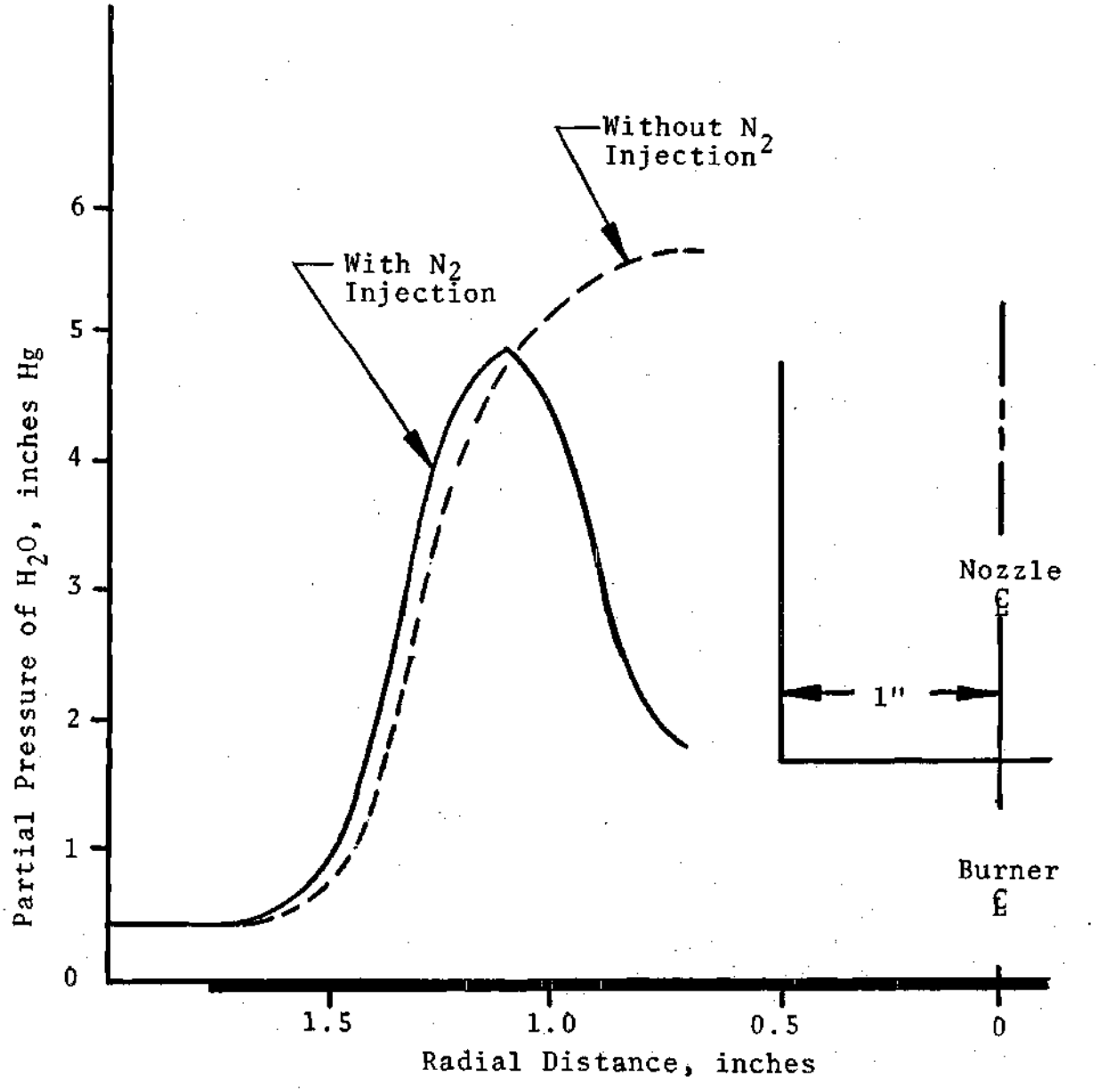

Figure 47. Concentration Profiles of H_2O; Air Flow Rate = 4.16 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 1.0 Inch Above Burner

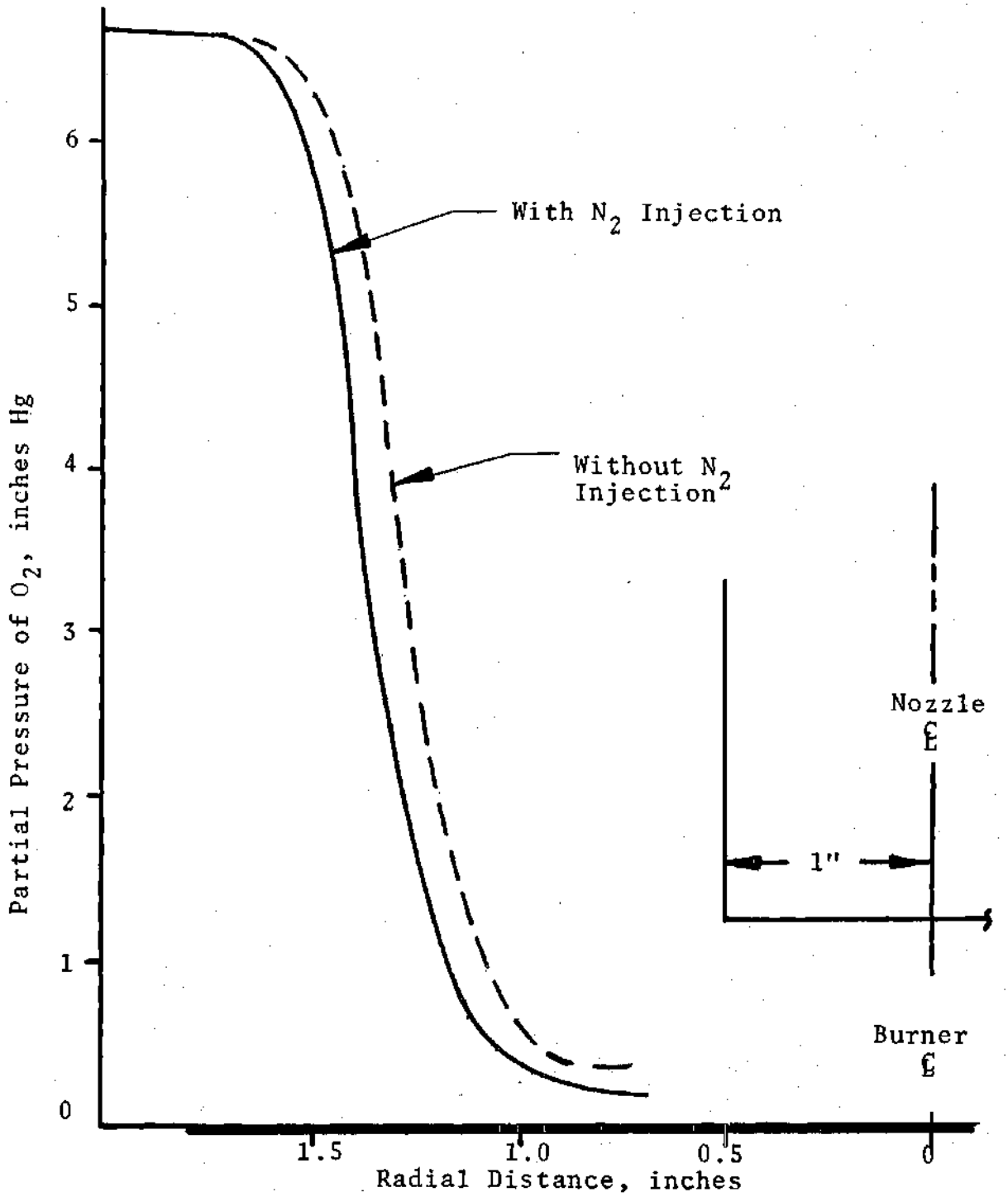

Figure 48. Concentration Profiles of O_2; Air Flow Rate = 4.16 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 1.0 Inch Above Burner

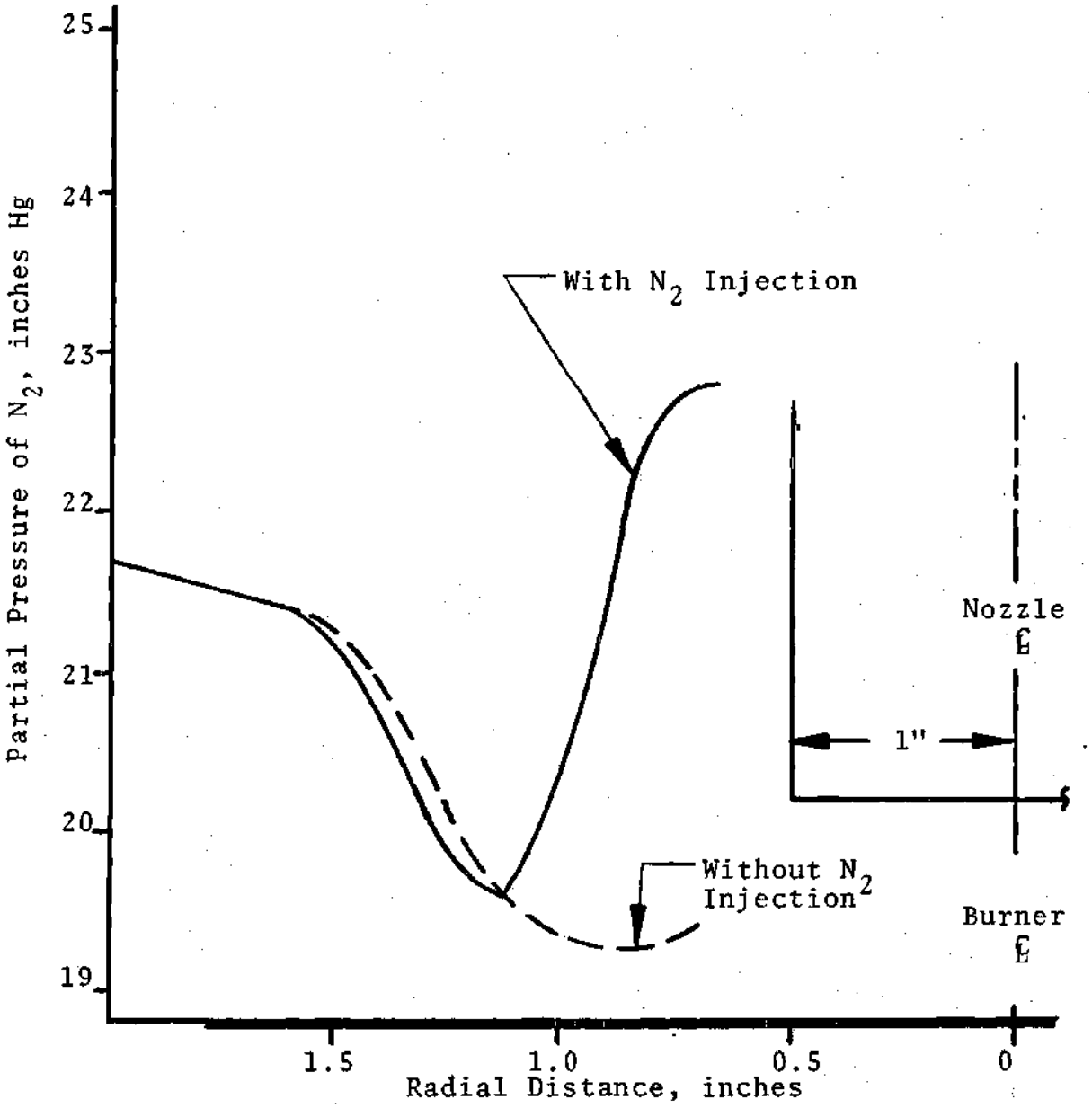

Figure 49. Concentration Profiles of N_2; Air Flow Rate = 4.16 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 1.0 Inch Above Burner

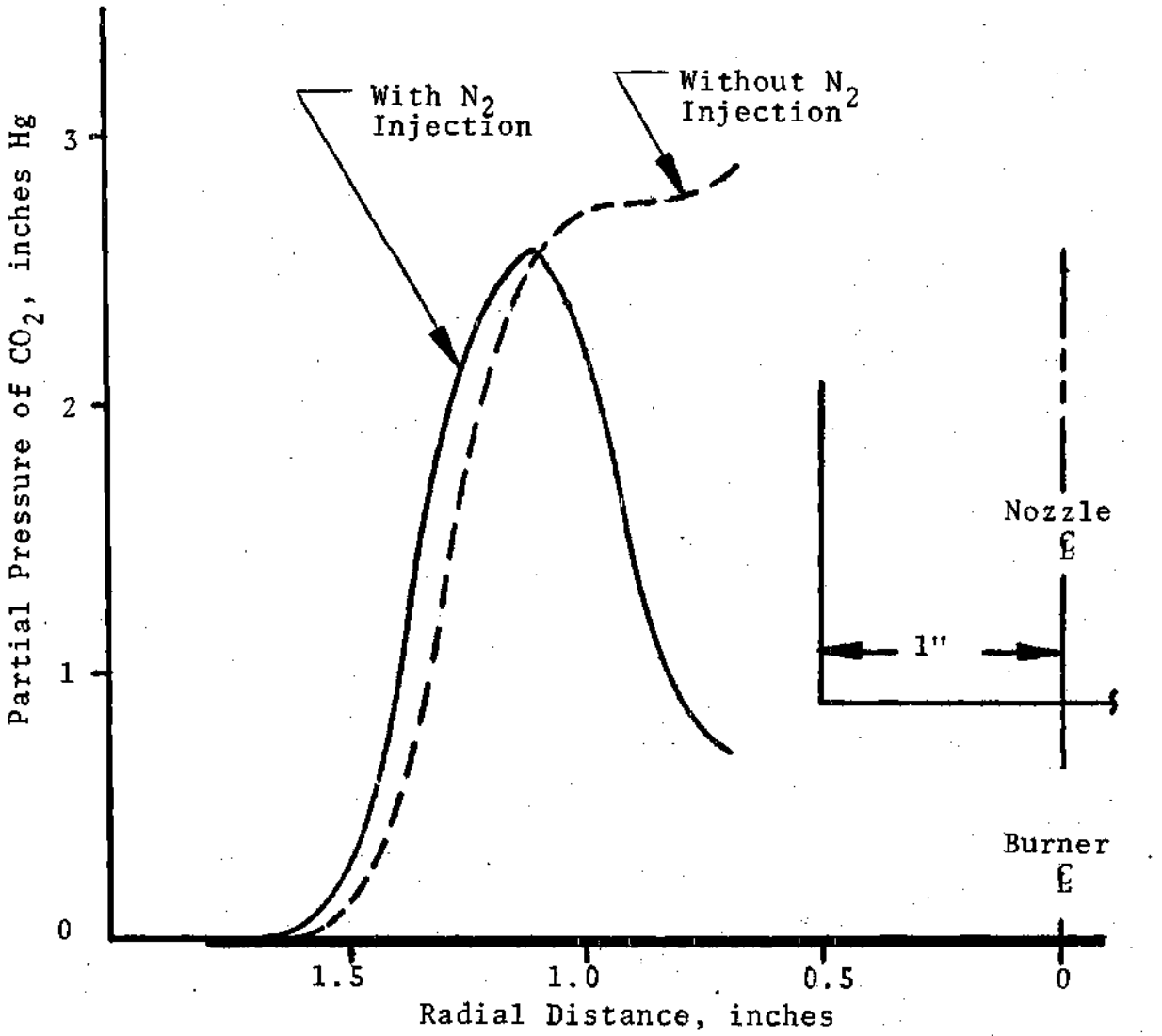

Figure 50. Concentration Profiles of CO_2; Air Flow Rate = 4.16 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.896, Sample Taken 1.0 Inch Above Burner

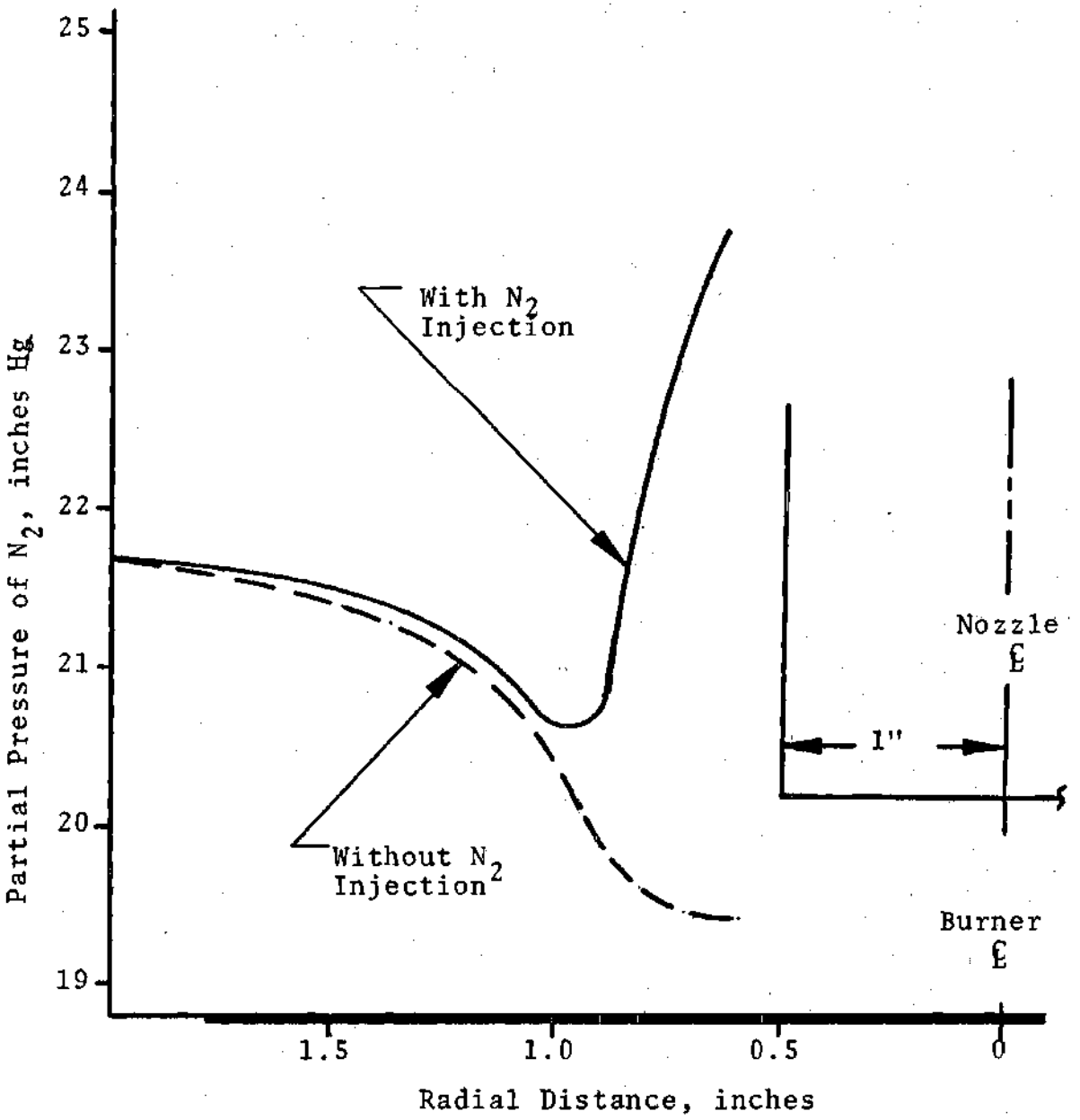

Figure 51. Concentration Profiles of N_2; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 1.50 Inches Above Burner

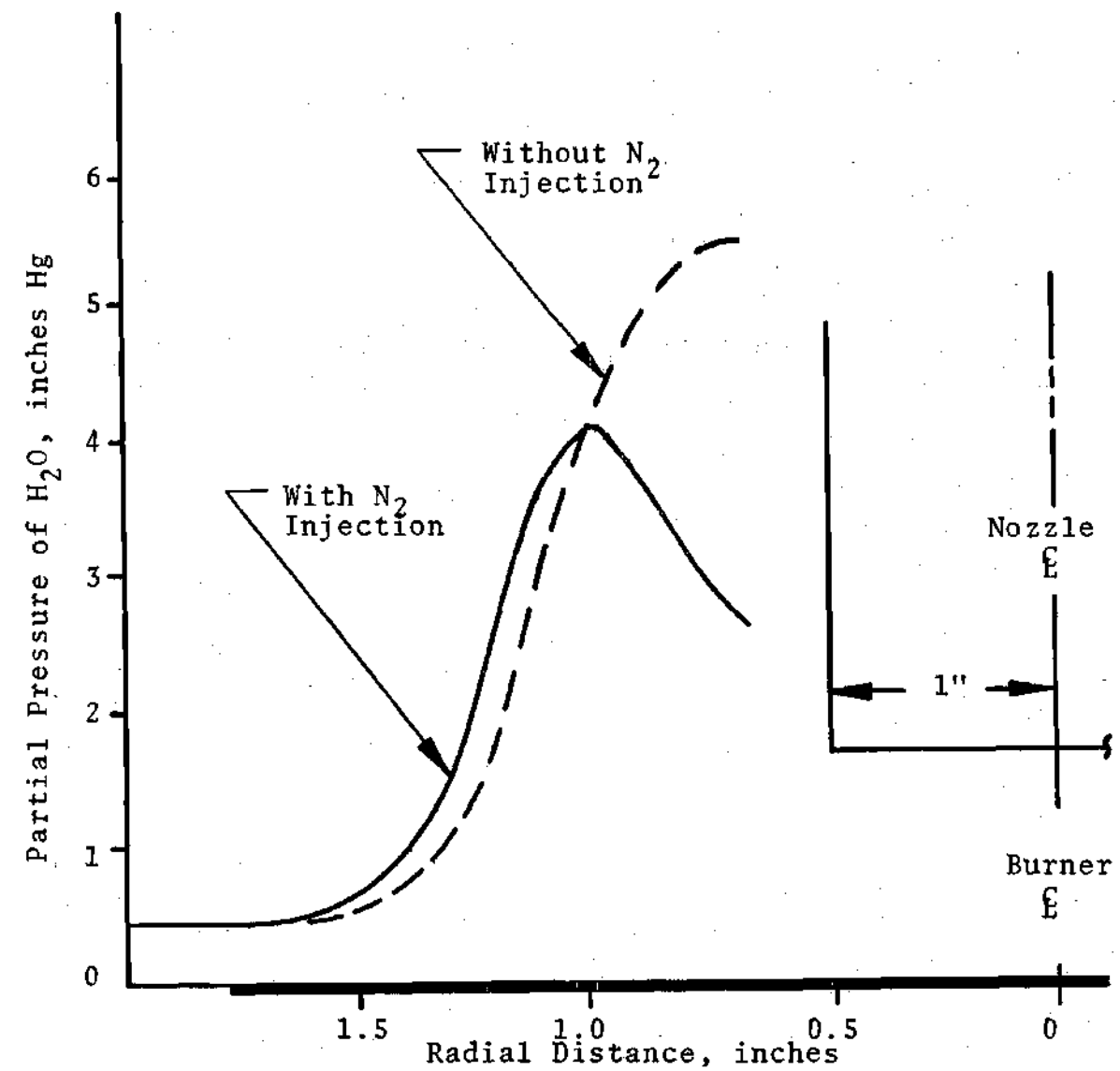

Figure 52. Concentration Profiles of H_2O; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 1.50 Inches Above Burner

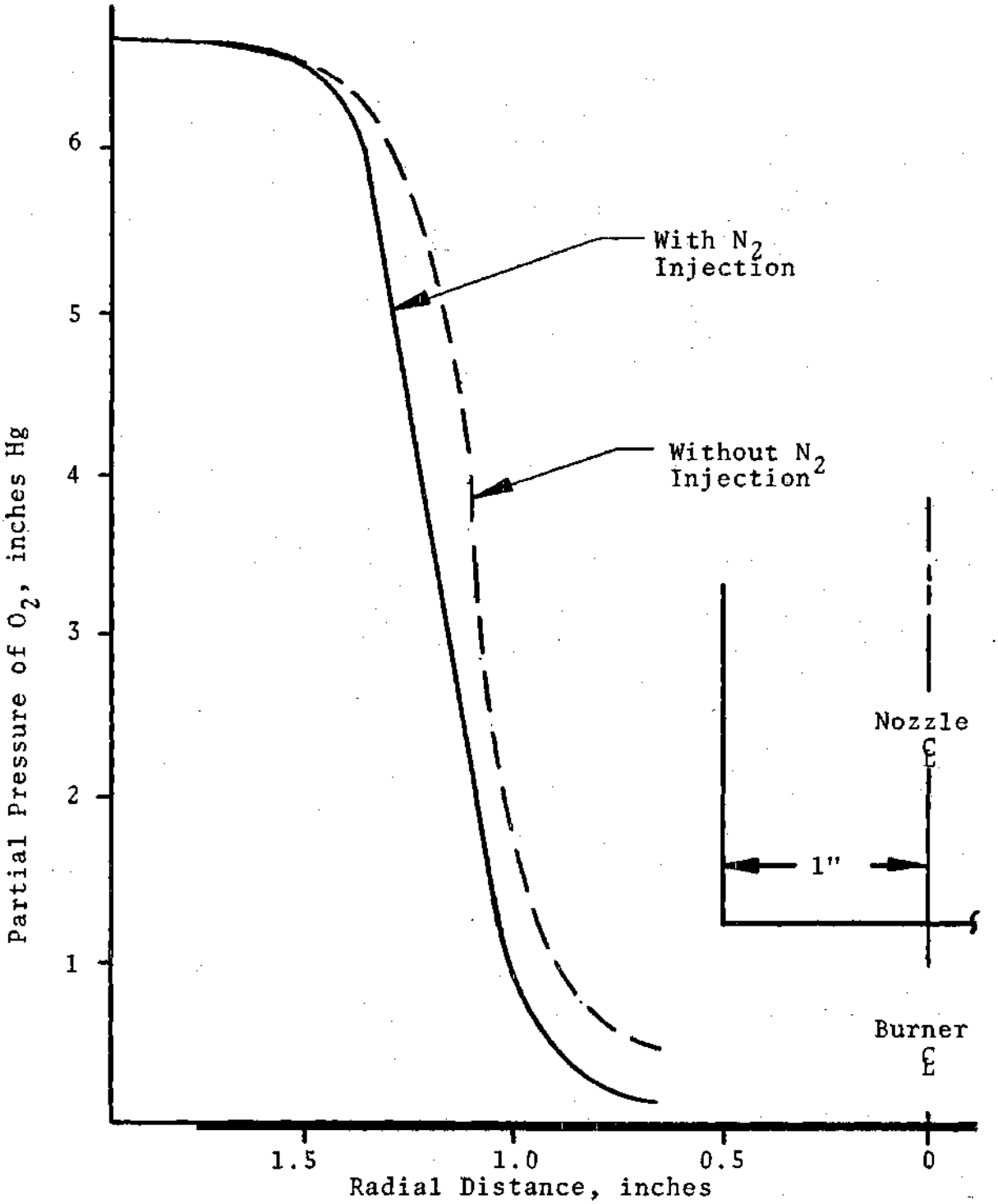

Figure 53. Concentration Profiles of O_2; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 1.50 Inches Above Burner

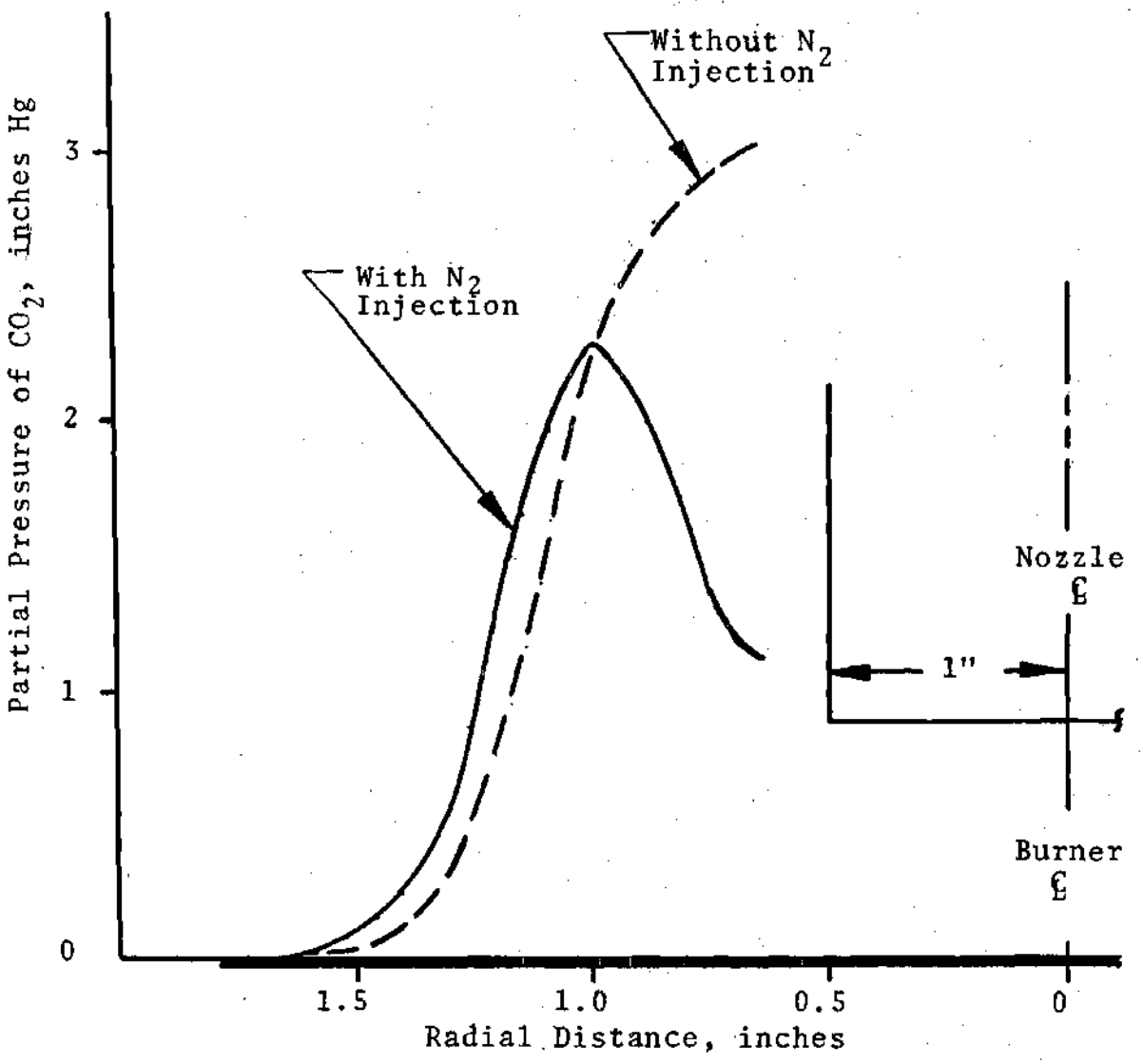

Figure 54. Concentration Profiles of CO_2; Air Flow Rate = 4.14 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 1.50 Inches Above Burner

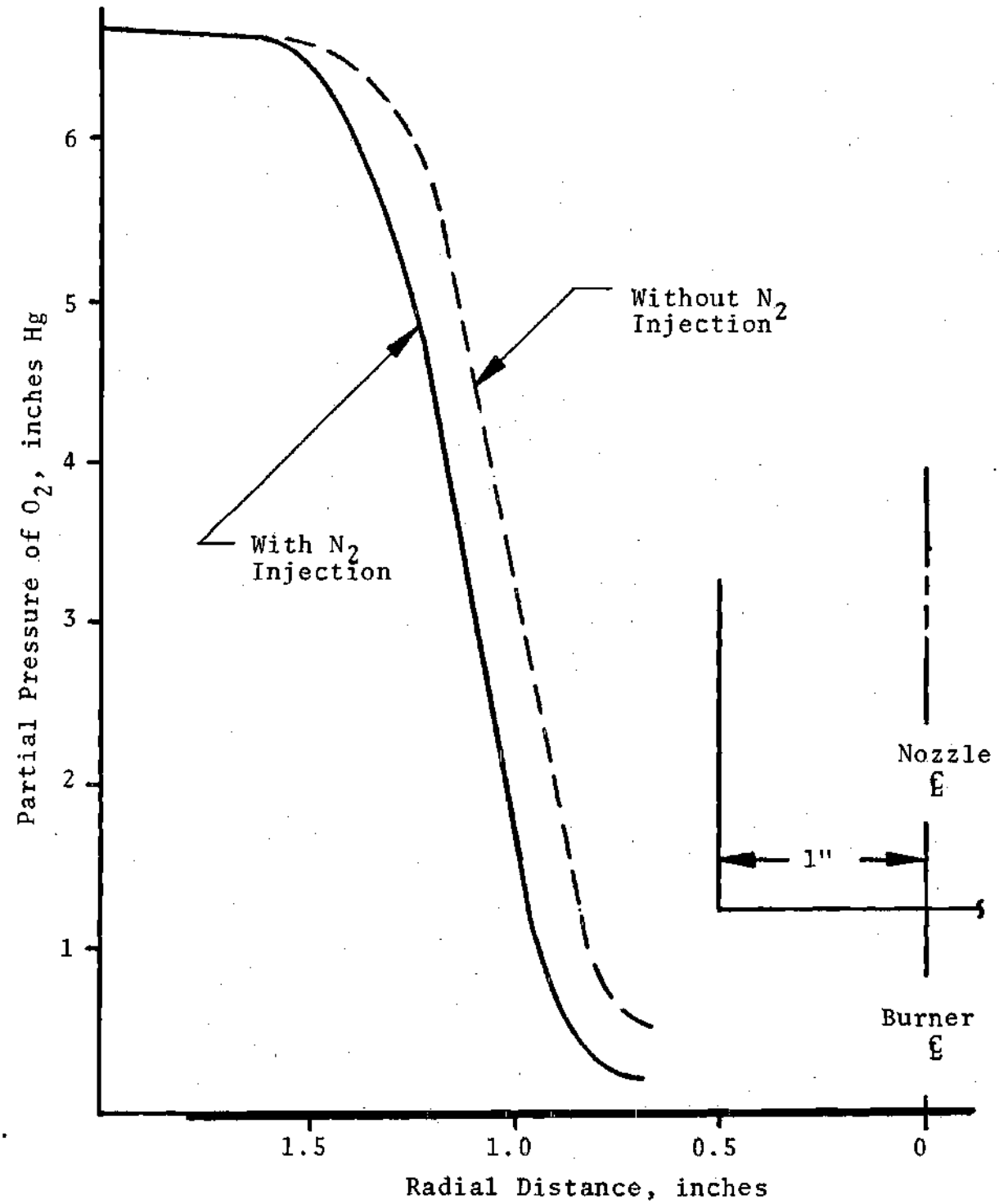

Figure 55. Concentration Profiles of O_2; Air Flow Rate = 4.15 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 2.0 Inches Above Burner

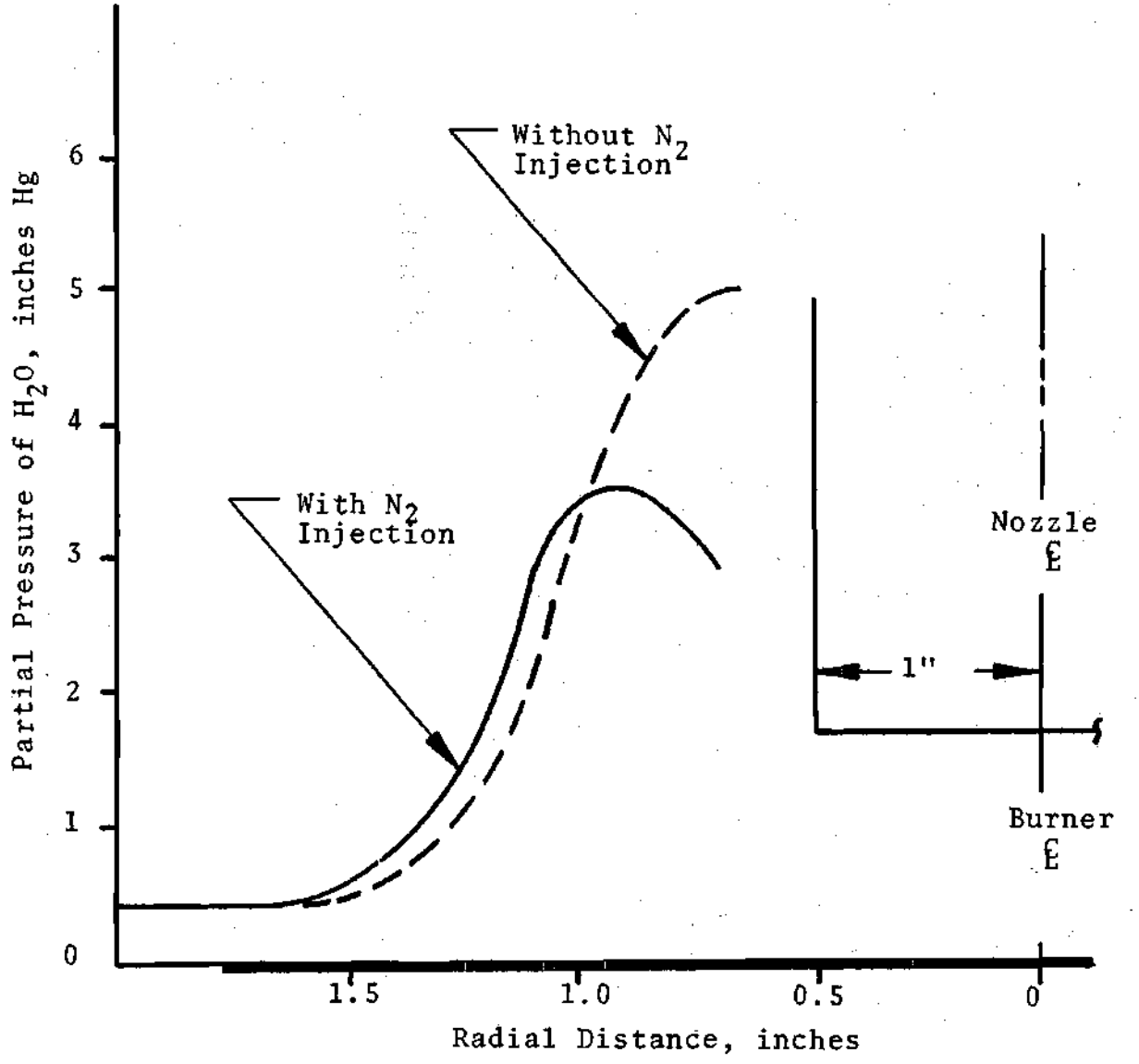

Figure 56. Concentration Profiles of H_2O: Air Flow Rate = 4.15 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 2.0 Inches Above Burner

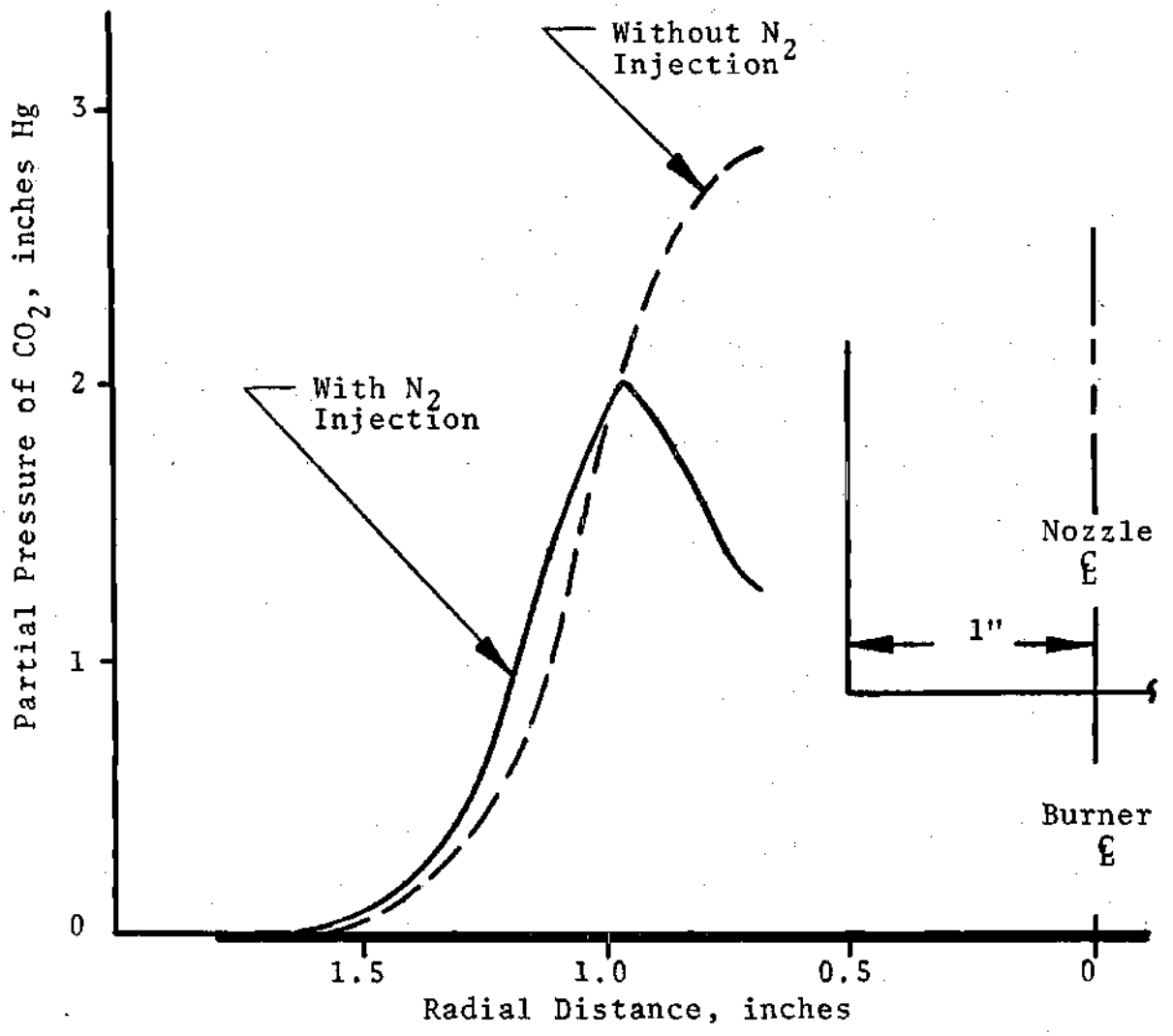

Figure 57. Concentration Profiles of CO_2; Air Flow Rate = 4.15 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 2.0 Inches Above Burner

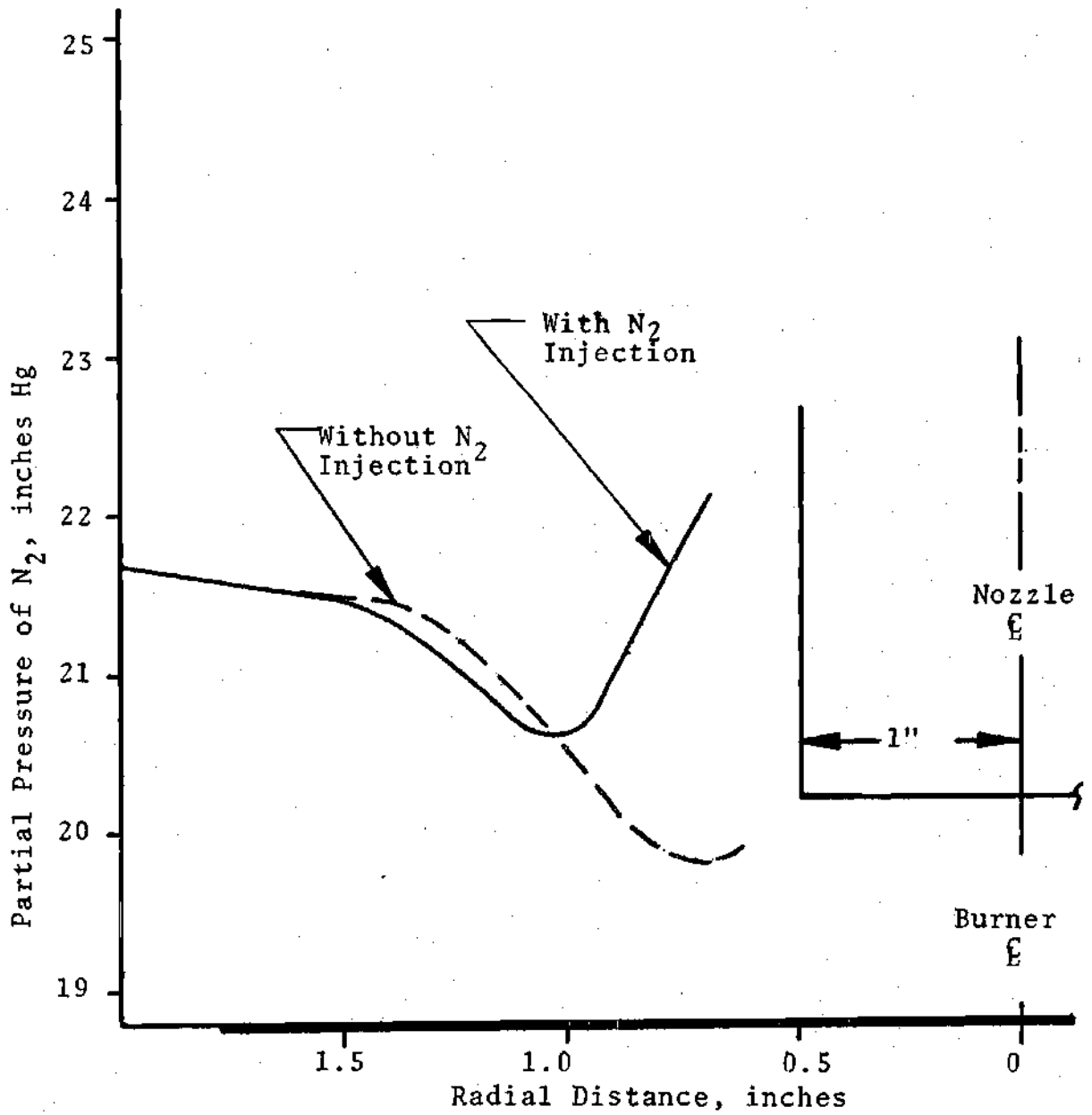

Figure 58. Concentration Profiles of N_2; Air Flow Rate = 4.15 lb_m/hr, CH_4 Flow Rate = 0.218 lb_m/hr, N_2 Flow Rate = 1.28 lb_m/hr, Φ = 0.900, Sample Taken 2.0 Inches Above Burner

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